AN EXAMINATION OF ALTERNATIVE FERTILIZER TRANSPORTATION, WAREHOUSING AND APPLICATION SYSTEMS FOR AGRICULTURAL COOPERATIVES

By

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CHAPTER I

INTRODUCTION

The difficulty of controlling cost in a dynamic industry where competitiveness and costs are changing over time has long been recognized. Conventional wisdom suggests that players who succeed in such an industrial setting are those who capture the opportunities presented by a new business environment while maintaining economic efficiency (Bello, Lohtia and Sangtani; Flint).

In recent years, one of the business challenges for fertilizer suppliers in the United States has been to keep pace with the changing business environment. The changes arise from changing demand, growing global competition, increased regulations in the industry for environmental and safety reasons, and improvements in the transportation and application methods.

The improvement in fertilizer distribution and application methods is by and large a reflection of changes in the physical condition and operating characteristics of highways, and changes in farm transportation and application equipment (USDA, Agricultural Cooperative Service). Changes in fertilizer demand and increased market competition are attributable to changes in farm application systems, and consolidation of farming business that has decreased the number of farms and increased the average farm size (Norton).

The changes in business environment have substantial impacts on input markets. Notable effects on agribusinesses that are directly involved with farm-level supplies include increased costs for transportation, warehousing and application systems. [1] Consequently the changes have resulted in massive restructuring of agribusiness firms to improve the use of resources through the formation of highly integrated associations (Williamson). The changes have also altered the pattern and the composition of fertilizer production and use.

Fertilizer use in the United States

Industry data show that between 1974 and 1988 commercial fertilizers provided 65-78 percent of nutrients required for crop production, with the balance coming from animal waste. The use of manure however decreased substantially in the 1990s as large livestock operations became increasingly regulated to reduce water pollution and other environmental damages (USDA, National Agricultural Statistics Services, 1993).

The application of anhydrous ammonia, urea ammonium nitrate (UAN) and urea increased in early 1980's because of the benefit from economies of size in transportation and storage, and the ease and accuracy of applying, and due to favorable crop yield response to nitrogenous fertilizers. Similarly, transportation, distribution, and storage economies promoted the use of fertilizers that contained more phosphate relative to normal super phosphates, especially diammonium phosphate (Tennessee Valley Authority).

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[1] Application systems are defined as mixes of fertilizers that are applied to provide nutrients requirements for a specific plant during the entire growth period.

More recently, the production of anhydrous ammonia in the U.S. has started to decline (Greg; Robinson). The decline is a result of increased price of natural gas, which serves as energy source and as raw material in the production of anhydrous ammonia. Natural gas accounts for about 72 percent of cash production cost, when natural gas price increase, production costs increase, and manufacturers can reduce its use thereby reducing the supply of fertilizers. Additionally, the American fertilizer industry competes with other major suppliers such as the Arab Gulf, Russia, Morocco, Indonesia and China. Thus, an increase in domestic production cost limits the ability of the industry to compete effectively in the world market. Consequently, the increased role of imported fertilizers, specifically dry fertilizers, has adversely affected the U.S manufacturers of nitrogenous fertilizers.

Domestic nitrogen fertilizer manufactures mainly produce anhydrous ammonia, which can be further processed into UAN and urea. Robinson indicates that anhydrous ammonia manufacturers began shutting down production in late 2000, by 2002, 45 percent of the U.S production was shut down (of which 21 percent permanently). Greg supports the relevance of increased role of imported fertilizers as he argues that increased production cost cannot be simply passed on to end-users because the world market sets the price. Recent industry statistics show that about 20 percent of traditional ammonia sales have been switched to dry forms. Though at present the switching rate is not alarming, increasing price and price volatility might make it a reality in the long run.

In addition to the market changes, environmental impacts from fertilizer production and use have also played significant roles in altering the composition of fertilizers used in agriculture. Policy makers have been striving to formulate policies that encourage the use of modern technology and an efficient environmental management system (EMS) to reduce emissions from fertilizes to negligible levels (Isherwood). Consequently, most of the activities related to transportation, storage, and application of fertilizers are highly regulated to minimize possibilities of spills leaching into water. In Oklahoma, the fertilizer act (OKLA.STAT. ANN. tit.2 § 8-61 *et seq*. (West 1997)) focuses on regulating the fertilizer industry. The Act requires fertilizer storage facilities to be constructed in such a way that injury to human and contamination of surface and ground water are prevented. Thus, suppliers invest substantial amounts of money to build containment structures to capture spills in loading and off-loading sites and in storage facilities. The overall effect of these policies is to reduce the quantity demanded when marketing cost and retail prices for the controlled fertilizers are elevated. The environmental compliance cost also contribute to the economies of size in fertilizer warehousing since the per ton cost of containment decreases as the size of warehouses increases.

The Oklahoma Fertilizer Market

In Oklahoma, as in many surrounding states, the size and structure of the grain marketing and input supplying firms were influenced by historical farm size and transportation systems. Historically, the trade territory of a grain elevator or supply firm often encompassed less than a 20-mile radius. As farm size has increased and truck transportation has improved, Oklahoma's agribusiness industry has undergone rapid consolidation. Cooperatives and other firms have pursued mergers, joint ventures and acquisitions in an attempt to gain economies of size and increased efficiency. Many cooperatives now encompass multiple locations and have a trade territory, which spans several counties as far as 50-miles apart.

Increase in farm sizes has also enhanced the importance of application services. Large-scale producers typically find it more economical for the input supplier to apply fertilizer using large-scale machinery (often referred to as floaters). Increasing theft of anhydrous ammonia (for use in manufacturing illegal drugs) and increased safety concerns have also contributed to reduce the use of anhydrous ammonia. Anhydrous ammonia is typically transported to the field in small tank trailers and is applied by producers. Producers shifting away from anhydrous ammonia often shift to dry or liquid forms of fertilizer that are contract applied by the agribusiness. The misuse of anhydrous ammonia is threatening and there is a growing concern that it might lead to the adoption of more stringent rules in its handling and use, or possibly a complete elimination in the future (Mid-Oklahoma Cooperatives).

Furthermore, the adoption of a newly developed nitrogen (N) management strategy has the potential to alter the composition of nitrogenous fertilizers applied and equipment used. For many years, the Oklahoma State University recommendation has been to determine fertilizer needs based on soil tests and realistic crop yield goals. However, more recently, researchers have found that available nitrogen varies from point-to-point (spatial variability) and from year-to-year (temporal variability). The new strategy advocates applying little or no fertilizer-N pre-plant to winter wheat, or with the seed, except for the N-Rich strip.[2] With this strategy, most of the N-fertilizer is top dressed after the crop has been grown and the farmer determines how much nitrogen to

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[2] N-Rich Strip is defined as spreader width application, the length of the field that receives enough pre-plant (or early season) fertilizer-N that the crop will not be limited by lack of N.

apply after assessing the difference in the N-rich strip and non-fertilized wheat (Johnson *et al.*). More importantly, the strategy of spring application has been recommended for all wheat producers, including the majority that uses constant rate application.

The ongoing fertilizer regulations in the industry have raised marketing costs. Agribusinesses are incurring extra costs because a significant investment is required to acquire specific assets that are consistent with fertilizer regulations. Cooperatives are pondering whether they can jointly finance the acquisition of such assets and share the use, which would also strengthen their market competition in terms of efficiency of the assets. However, this arrangement requires centralization of the assets so as to maximize use among the beneficiaries (Eldon).

Fertilizer warehousing and application services are also capital-intensive activities. Environmental regulations that require containment structures to capture spills have significantly increased warehouse construction costs. There is also a significant economies of size in containment engineering with the per ton cost of containment decreasing as the storage size increases. Fertilizer application equipment also involves significant capital expenditures with the cost of a single applicator often exceeding $200,000 (Mid-Oklahoma Cooperatives). The high fixed costs associated with application equipment provide incentives for the agribusiness to maximize annual use and minimize transportation and other down times.

The increase in the price of natural gas and corresponding increases in prices of nitrogen fertilizers have triggered cooperatives and other firms to assess the feasibility of purchasing fertilizers from alternative sources. In general, a fertilizer plant located at Enid is a major supplier of anhydrous ammonia in Oklahoma. However, Shortfalls in domestic production of anhydrous ammonia has caused some of the local demand to switch from the anhydrous ammonia to dry forms of nitrogen that are imported via the Port of Catoosa. Some agribusinesses have also opted to ship fertilizers from alternative suppliers in other states. Isherwood indicated that cost-effective road transportation is limited to a distance of approximately 100 miles beyond which rail transportation becomes more cost-effective. The challenge, which cooperatives and other firms face, is to choose the most efficient means to transport fertilizers from alternative sources and to carefully reexamine supply schedules. In economic terms such a choice encompasses both the economies of size and travel distance.

Domestic production of fertilizers has become erratic and intermittent. The loss of secured domestic supplies has forced agribusinesses to rely on foreign suppliers. Therefore, most firms put more emphasis on warehousing to avert unpredictable shortfalls in supply. However, the construction of warehouses is a big capital investment and it needs a thorough examination of storage demand across service regions to determine optimal sizes and locations.

Oklahoma Cooperatives are also striving to coordinate the distribution of fertilizers to farmers, which has been purely based on informal scheduling of work orders. Plans to coordinate scheduling of work orders are under way. A prior assessment of cost components and operational efficiencies associated with fertilizer application systems are crucial for successful coordination.

Overall, the above trends have led cooperatives and other farm supply businesses in Oklahoma to explore more efficient structures for fertilizer warehousing and application services. Several agribusinesses are considering the construction of centralized large-scale fertilizer warehouses. These firms are also trying to determine the optimum complement of application equipment and the advantages and disadvantages of having application equipment in central locations.

Problem Statement

The farm input business is changing dramatically. Environmental concerns with regard to fertilizer use, changes in the market structure, and competition in the agrochemical industry have changed the way fertilizers are procured, distributed and applied in Oklahoma.

The increased role of imported fertilizer, coupled with safety and regulatory issues, has created a drive that encourage producers to shift from anhydrous form of nitrogenous fertilizers toward dry and liquid forms. Advances in variable rate application technology may also influence a shift toward spring applications of liquid formulations. The handling and application of dry, liquid, and anhydrous ammonia require different facilities and equipment. It is possible that operating costs may vary substantially across the application systems. Therefore, it is crucial to identify a least-cost way of satisfying wheat nutrient demand, which is a major crop in Oklahoma, and to examine the impact of this shift on operating cost of fertilizer supply firms.

Due to consolidation of fertilizer supply and application firms, many agribusinesses are examining the advantages and disadvantages of centralizing their warehousing and application operations. Thus, it is also important to evaluate the impact of centralized warehousing and application on total cost of a typical multi-location fertilizer supply firm.

Increase in farm size has enhanced the importance of application services. Large-scale producers typically find it more economical to apply fertilizer using large-scale machines. It is imperative for fertilizer supply and application firms to understand the impact of farm size on the use-efficiency of large machines.

Motivation and Objectives

Contemporary studies, such as Hammond, Hammer, and Dahl, Schullze and Akridge, Scott, and more recently, Dahl, Cobia, and Dooley have not considered the impact of centralized warehousing and application equipment on the operating cost of fertilizer-retail firms. Thus, issues related to economies of size, coordination of fertilizer storage and applications, as well as changes in types of fertilizers used, have not been addressed. The objectives of this study are:

i) To evaluate how a shift from anhydrous form of nitrogen fertilizer towards dry and liquid forms will affect operating cost of a typical multi-location fertilizer supply agribusiness.

ii) To compare current fertilizer warehousing and application systems for representative cooperatives located in central Oklahoma with the optimal structure evaluated based on coordinated systems and using the same forms of fertilizer.

iii) To compare costs between centralized and non-centralized operations under different application systems and assess whether it is feasible for studied cooperatives to opt for centralized warehousing and application.

iv) To determine the impact of farm size on the use-efficiency of large-scale machines.

Anticipated Contribution

Results generated from this study will aid fertilizer supply cooperatives and other agribusinesses in the wheat industry to identifying more efficient fertilizer warehousing, transportation and application systems. Results will give insights into the likely effects of eliminating anhydrous ammonia on the fertilizer warehousing and equipment systems as well as efficiency differential for using large-scale machines in large versus small fields. Results will also provide insights into how a shift toward spring application of nitrogen fertilizer (which is typically applied as UAN) would impact on optimal equipment compliment and total application costs. The cost impacts on the fertilizer warehousing-transportation-application system, along with price differentials between dry and liquid formulations are important considerations that should be included in the cost/benefit evaluations of the new systems involving spring nitrogen applications.

Organization of the Study

This study is organized into six chapters including this introduction. Chapter two summarizes a conceptual framework underlying the analytical model used in the study. Facility location models and their applicability to the identified study problems are reviewed in chapter three. Data sources, collection methods and the empirical models are presented in chapter four. A comprehensive summary of empirical models, basic assumptions used, and technical description of equations and variables specified in the models are outlined in Appendix 1. Chapter five summarizes empirical findings and their implications. Chapter six gives concluding remarks, study limitations and suggestions for future research.

CHAPTER II

CONCEPTUAL FRAMEWORK

Supply chain management is widely acknowledged in literature as one of the best strategies to make a supply network more competitive (Romano). The strategy is essential for enhancing resource-use efficiency, improving relationship between supply networks, precise planning and control of materials and information flow across the supply chains, and minimizing transaction time (Cooper and Ellram; Ellram; Mason *et al.*).

Romano has indicated that existing literature emphasizes three closely interrelated elements that need careful examination to understand how logistic processes can be designed and managed across a supply network. The elements include drivers (managerial variables) that govern the processes, and coordination as well as integration mechanisms that contribute to determine the impact of the drivers on business processes and outcomes.

Theoretically, there are many coordination and integration mechanisms that could be used in the supply chain management. For example, Mason *et al.* have identified integration of warehousing and transportation systems to be one of the strategies to reduce suppliers' operational costs, thereby reducing product cost for end users. Chiang and Russell suggest integrating purchasing and routing as a potential strategy to reduce annual operating cost. Herer, Tzur, and Yücesan underscore a need for establishing transshipment centers for monitoring movement of stock between locations and provision of back-up materials to meet excess demand that could arise when demand at particular locations turn out to be higher than expected.

In general, supply chain management is a holistic cost reduction approach that encompasses inventory management, transportation and warehousing control, order processing, and other processes such as customer relations' management, product development and commercialization, and quality control.

The analytical model adopted in this study focuses on the concept of supply chain management with a particular attention to integration of transportation, warehousing, purchasing, and application of fertilizers. This conceptual framework is advocated because in the fertilizer industry consolidation of materials in warehouses and centralization of application equipment has emerged as an effective cost-saving method due to high percentage of total distribution or costs associated with transportation and fixed-asset charges (Mid-Oklahoma Cooperatives).

Operationally, cost reduction in this framework has been most successfully analyzed using mathematical programming models that provide a reasonable basis for evaluating alternative set-up and ensuring that facility locations are determined at distinct points that minimize combined costs. Discrete and continuous mixed integer programming models have been widely used for this purpose (Cappanera, Gallo, and Maffioli; Dasci, and Verter; Goldengorin, Ghosh, and Sierksma).

Continuous models assume that clients are spread over a known market area and prescribe the best possible service region for each facility to be established. Details regarding modeling procedures are summarized in Dasci and Verter. Problem formulation in this case always assumes continuous and uniform dispersion of demand in each region, and a specific shape of service regions (either circular, hexagonal, square, diamond, or triangular). Nevertheless, a major problem with this conceptualization is that demand points are neither regular nor continuous in space.

In contrast to continuous models, discrete facility location models treat demand as a set of discrete points, and assume movements follow Euclidean metrics and that the demand point locations, as well as the flow of materials and equipment between all origin-destination pairs, are specified (Campbell). Therefore, discrete modeling more closely reflects the structure of the fertilizer distribution and application.

In the fertilizer industry, the supply chain entails transportation of fertilizers from manufacturers or importers to storage facilities and finally to producers in known service regions. In addition to fertilizer distribution, most of the retailers also own fertilizer applicators that are rented to individual producers and other firms. Thus, a significant cost reduction in the supply chain could be achieved through efficiency that might be apparent in coordinated transportation, warehousing, and application activities. Therefore, a cost minimization model was developed to represent a total coordination of business activities because improving efficiency is a goal that cannot be pursued in isolation.

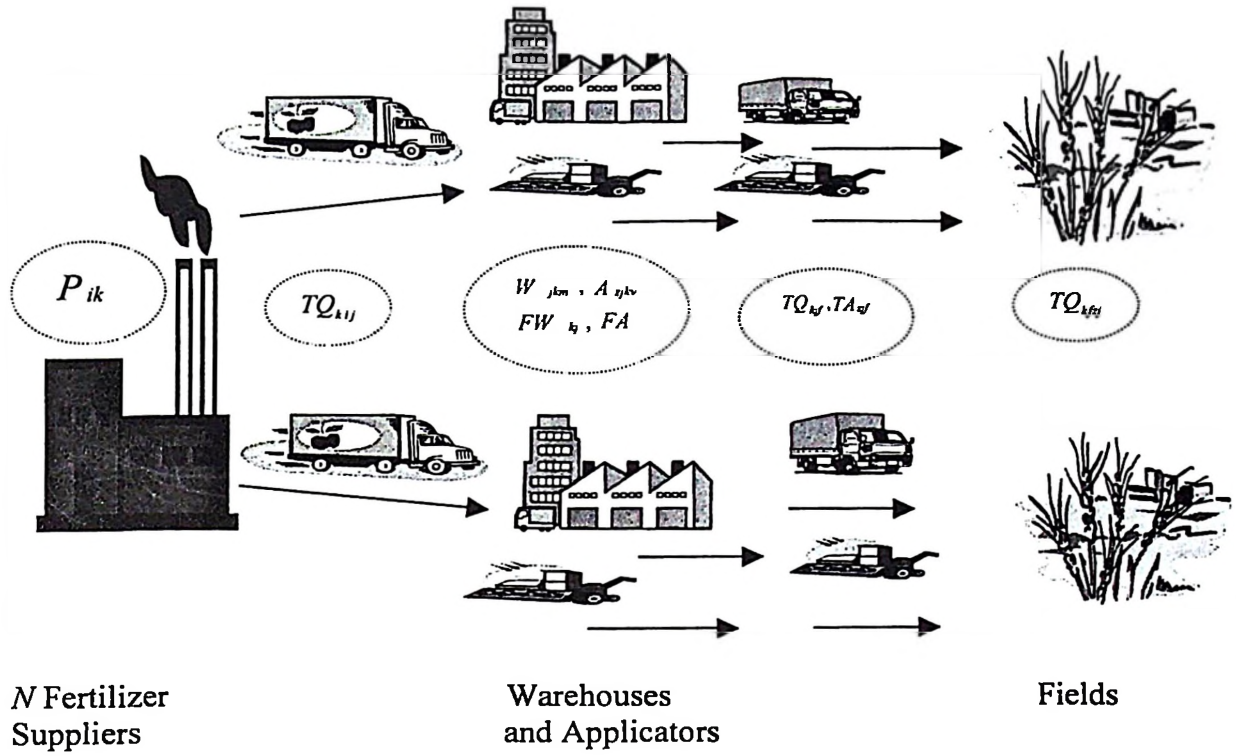
The analytical model for this study is a capacitated discrete mixed integer-programming (CDMIP) model. The model requires simultaneous reduction of all cost-components associated with fertilizer transportation, warehousing, and application subject to meeting supply, demand, and facility and equipment capacity constraints. The costs are:

i) Those associated with shipping fertilizers from potential sources to alternative warehouse locations and finally to application points,

ii) Fixed-charges for alternative warehousing,

iii) Fertilizer application and fixed-charges for application equipment.

The cost structure discussed above is detailed in Figure 1 below:



Where:

P_{ik} is a Plant *i* producing a fertilizer type *k*.

TQ_{kij} is total cost for shipping *Q* quantity of fertilizer type *k* from plant *i* to warehouse *j*.

W_{jkm} is a warehouse *j* for storing fertilizer type *k* with a maximum storage capacity *m*.

A_{zjkv} is applicator *z* from warehouse *j* for applying fertilizer type *k* with a seasonal material capacity *v*.

FW_{kj} is annual cost for storing fertilizer type *k* in warehouse *j*.

FA_{zk} is annual cost for using applicator *z* to apply fertilizer type *k*.

TQ_{kjf} is total cost for shipping *Q* quantity of fertilizer type *k* from warehouse *j* to field *f*.

TA_{zjf} is total cost for shipping applicator *z* used to apply fertilizer type *k* from warehouse *j* to field *f*.

TQ_{kfzj} is total cost for applying *Q* quantity of fertilizer type *k* at field *f* using applicator *z* from warehouse *j*.

Figure 1 **Transportation, warehousing, and application costs for different types of fertilizers**

Basic Formulation of the Mathematical Programming Problem

In brief, given a fixed-cost F_j and a capacity constraint λ_j of the j^{th} facility, the cost minimization function Z for the i^{th} activity linked to the j^{th} facility, with a variable cost C_{ij} and activity level Q_{ij} is mathematically given as:

(2.1) $\min\limits_{Q_{ij}, Y_j} Z = \sum\limits_i \sum\limits_j C_{ij} Q_{ij} + \sum\limits_j F_j Y_j,$

Subject to:

(2.2) $\sum\limits_i Q_{ij} \geq D_j \quad \forall\, j$ (demand constraint)

(2.3) $\sum\limits_j Q_{ij} \leq S_i \quad \forall\, i$ (supply constraint)

(2.4) $\sum\limits_i Q_{ij} \leq \lambda_j Y_j, Y_j \in \{0,1\}, \forall\, j = 1, 2, ..., n$ (capacity constraint)

(2.5) $Q_{ij} \geq 0$ (non-negativity condition)

The problem set-up ensures that a cost C_{ij} is incurred only if a facility Y_j is acquired. The D_j in equation 2.2 and S_i in equation 2.3 are aggregate demand and supply, respectively. The generalized equations 2.1 - 2.5 are fundamental equations for the proposed CDMIP model. Justifications for this choice are described in chapter three. A detailed structure of the model is presented in chapter four.

CHAPTER III

LITERATURE REVIEW

Introduction

The literature on facility location models is enormous and there are a variety of facility location models and applications, nevertheless, all models require four basic elements. First, a set of locations where the facility may be located and corresponding acquisition cost. Second, a set of demand points (clients) to be assigned to a facility. Third, a list of requirements to be met by the facility and assignments of demand points to facility. Finally, a function that associates to each set of facilities the cost or profit incurred if the facility is acquired. In general, there are many criteria that are used to classify facility location models. Bumb, for example, revealed that location models can be classified as discrete or continuous, deterministic or stochastic, capacitated or uncapacited, and dynamic or static.[3] This section attempts to review theoretical approaches useful to model facility location. However, given the abundant literature and the diverse classification of the location models, the focus is narrowed to approaches that could be used for the problem defined in chapter one.

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[3] In contrast to continuous models, discrete models are models in which sets of demand points and facility locations are finite. A model is deterministic if all the data used are exact and is stochastic if some parameter values are probabilistic. Capacitated models, are models in which upper bounds are imposed on the number of clients that a facility can serve, otherwise it is uncapacitated. Dynamic models as opposed to static models are models in which time element is explicitly represented.

Overview of Facility Location Models

Location problems involve a decision over number and location of the facility in relation to demand and supply points, a largest group of which are those with the objective to minimize travel time, cost, or maximize net revenue. Most of these models are static in nature and assume static equilibrium (Beckmann, 1968 and 1987). However, there are dynamic models as well, but the dynamics are only exogenous, i.e. choice variables might change but the systems stay in equilibrium. The problem is normally to locate the facility spatially in such a way that demand and other constraints are satisfied. This problem has been analyzed using different modeling approaches such as uncapacitated facility location models, transshipment models, integrated models, simulation models, mixed integer models, or a combination of these models. A detailed discussion for each of these model classes is presented below.

Uncapacitated Facility Location Models

Uncapacitated facility location problem is one of the most studied problems in operation research. The conceptual framework dates back to 1960's (Balinski; Kuehn and Humberger; Manne; Stollsteimer). In its simplest form, a problem is to find optimal locations at which to place facilities to serve a given set of client locations. The set-up of this problem requires some prior information on a set of locations at which facilities may be located, acquisition costs at each location, and distances between locations. Also a constraint is normally imposed so that each client must be assigned to one of the facilities, thus, incurring a given cost. The objective is to minimize total cost. Empirically, the model incorporates travel distance, time, and cost, as well as other relevant factors. The solution is normally obtained iteratively, starting from a single location and then changing the location until the optimal solution is obtained.

A major limitation with this modeling approach is that the problem becomes difficult as the number of facilities become large. Literature indicates that the problem has remained difficult until the beginning of the 1990's when an exact algorithm for solving it was developed (Rosing; Baumol and Wolfe). Tembo reveals that the solvability of such models is partly affected by the presence or absence of economies of size and locations' cost differentials. In general, the difficulty in solving the problem has made it attractive to operational researchers. Consequently, literature reviewing facility location algorithms is immense. Bumb; Chern and Polopolous; Francis, McGinnis, and White; Kamal and Vaziran; Krarup and Pruzan; Ladd and Halvorson; Polopolous; and Tansel, Francis, and Lowe are part of this modeling effort. To date, the framework is increasingly becoming applicable to a number of industrial situations such as locating proxy servers on the web, placement of factories, fire stations, and hospitals.

Transshipment models

A facility location problem can also be analyzed with a transshipment model. The model is an extension to basic linear transportation problem.[4] The model determines the optimal facility location, size, and numbers with respect to either distribution or assembly activities. One way to approach this problem is to classify each production and consumption point as a possible transshipment center and then evaluate how combined assembly and distribution cost changes when the location is altered. The model is advantageous because it allows assessment of both assembly and distribution system.

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[4] In linear transportation model, direct shipments occur between a supply node and a destination node.

This mode of cost reduction has been recognized in flour milling, milk, and livestock industries (Hoover; King and Logan; Wiles and Brunt).

The transshipment approach has three major limitations. In terms of estimation, the model is solvable as a linear programming problem if the cost functions associated with supply links are linear in terms of cost per unit item shipped. Empirical evidence reveals that in many cases, transport cost normally tapers with increasing haulage distance and decreases with respect to haulage quantity for any given distance. Thus, a relationship between transport cost and haulage distance is concave and a relationship between transport rate and quantity shipped is convex, which suggests non-linear cost functions (McCann). Another weakness of the approach is the assumption that shipment occurs simultaneously, which cannot account for costs due to timing such as holding cost. The assumption of static demand constitutes another weakness because demand might be stochastic and there are possibilities of stock out-situations in which demand exceeds inventory level.

Integrated Models

Alternatively, a facility location problem can be analyzed using integrated facility location models. This class of models allows comparison of tradeoff between the cost of modifying the underlying supply network and attempting to add new facilities. The comparison entails choosing the best option among different investment plans that leads to efficient allocation and utilization of resources. Pioneers of integrated models suggest that the models could be used in a variety of applications such as pipeline distribution systems, transportation systems, power transmission networks, and hub-and-spoke networks.

Berman, Ingco and Odomi, and Melkote and Daskin are among the empirical studies that used integrated models. Despite the fact that most of the applications have been in the industrial sector, the framework can also provide a sound basis for addressing agribusiness problems. An ideal case would be a situation where firms have established permanent supply links from a central business location and modifying the structure might be a cost-saving way to improve efficiency than attempting to restructure it. However, modeling demands in-depth, accurate, and up-to-date data for each activity and linkage.

Simulation Models

Simulation models (scenarios evaluations) are also used to model facility location problems. The models are simply used to calculate the effects of altering facility locations on the cost and service level and are not designed to guide researchers to optimum or near-optimum solution. The effects are identified through testing various numbers and locations of facilities. Traditionally, the calculations have been done using an iterative process in which cognitive skills of researchers are merged with the computational capacity of computer programs to identify facility locations. In the computation process researchers' skills facilitate identification of possible facility locations and the computer solves the corresponding allocation problem to determine optimal customer assignments to facilities, product or equipment flows through the system, and overall cost. The process normally stops when the analyst is satisfied with the computer output (Robinson Jr., and Swink).

Dynamic approaches are now becoming popular to account for stochasticity and feedback. The dynamic models attempt to relax the assumption that facilities chosen will always operate as planned. A major drawback in using dynamic simulation models is its complex nature in terms of formulation and solvability.

Mixed-Integer Programming Models

Mixed-integer programming is also widely used to model facility location problems. The mixed-integer models are constructed to minimize the total of location and transportation costs of satisfying the demand for some commodity or service. The total cost includes set-up cost for establishing the facilities and transportation cost between facility and customers (Averbakh *et al.*; Köksalan, Süral and Kirca).

Mixed-integer programming is an optimization technique that relies on implicit enumeration methods to search for the least-cost network design. The approach does not allow researchers' cognitive abilities to directly influence the number of iterations, which is different from simulation and transshipment models in this regard. The approach is also superior because it uses fixed charges that are amortized over the useful life of facilities. In general, mixed-integer models give better results for policy and industrial use (Faminow).

Technically, solving a linear programming (LP) problem is relatively easier than solving a mixed-integer programming (MIP) problem. However, researchers have now developed different kinds of algorithms for solving the MIP problems. Hung and Hu for example have developed an algorithm that uses shadow price information provided by the LP problem iteration to convert an MIP problem into solvable LP problem using a set-up decision computation. Tembo indicates that another alternative to solve mixed-integer problems is through the use of efficient network codes, which uses branch-and-bound procedures.

MIP has been extensively used to solve plant location and machinery selection problems. Köksalan, Süral, and Kirca used a MIP model to identify an optimal location for a large beer company in Turkey. In this application, the authors determined a location for opening additional breweries in the existing production set-up. The objective was to minimize transportation cost for shipping malt from sources to the breweries and shipping beers from breweries to different consumption areas. Camarena, Gracia, and Sixto have used MIP to realize the benefit of high capacity but expensive machines that could not be used economically on individual farms. They developed a multi-farm machinery selection model to minimize total mechanization costs. Ghassam *et al.* used a MIP model to select optimum harvesting method and machinery systems for mixed crop system to maximize farm profit. Saadoun used MIP to simultaneously select machinery sets and cropping pattern to be adopted on a specific piece of land.

Other Modeling Approaches

The plant location problem can be conceptualized and analyzed using different approaches. Some of the approaches have advantages over others. However, all the facility location models focus on modeling a facility's set-up cost as a function of its location and ignore the dependency of the facility on the number of customers served by the location. The traditional formulations discussed above are based on the assumption that a facility will always be large enough to serve all customers.

Averbakh *et al.* propose the adoption of facility location model with demand-dependent set-up cost that allows some locations to have large and others to have small facilities based on relative changes in demand. On the other hand the assumption that the established facilities can provide adequate services to all demand points can be challenged because facilities "failure", is a frequent phenomenon and there is a tradeoff between day-to-day operating cost and the expected cost taking failure into account. A failure can result from congestion in the system especially when demands for the facility with limited resources arise simultaneously. The tradeoff might offer an incentive for firms to incur costs that are much greater than the optimal levels so as to hedge against occasional and unpredictable disruptions in supply. Accounting for facility failure is important in agricultural science because machinery failure constitutes a major problem in planning farm operations. Three types of models have addressed this modeling weakness, which include queuing-based location models that consider consumer waiting for service (Larson, 1974 and 1975). Others are maximum expected covering location models, which assume a constant system-wide probability of failure, and maximum availability location models, which allow facility availability to vary among service areas (Daskin; Revelle and Hogan). Accounting for these weaknesses, however, might be difficult because of data problems and lack of computer specific skills or computer programs.

The Choice of the Analytical Model

In general, the choice of the analytical method for this study was jointly determined by the primary objective of the study and the nature of the data used. The empirical model for this study is a CDMIP and is partly described in chapter two. The model was capacitated because upper limits were imposed on warehouse storage capacities as well as on capacities of the fertilizer applicators. The model was discrete because it was assumed that fertilizer demand was concentrated in discrete points in each demand location.

The MIP was selected because its enumeration procedures do not allow researchers to directly influence the number of iterations. The model also handles discrete and continuous variables. Therefore, similar to a transshipment model, the MIP model can determine optimal location and size of a facility. Additionally, MIP models can be structured to accommodate scenario evaluations and dynamic effects, for example, scenario evaluations can be handled using "looping" procedures, and dynamic effects can be traced using time series data or stochastic approaches. MIP is also superior to other approaches because it uses fixed charges that are amortized over the economic life of facilities. Therefore, the model permits valuing machinery capacity and opportunity costs for funds and it gives better results for planning purposes. The model was formulated to address the problem of fertilizer equipment failure, here in referred as "machinery failure".[5] The model is fully detailed in chapter four.

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[5] Machinery failure was assessed using probabilities, which were estimated using a standard formula proposed by the American Society of Agricultural Engineers. However, it was difficult to generate stock-out probabilities for warehouses because time series for fertilizer demand were not available.

Methods Used to Estimate Machinery and Warehousing Costs

Cost data are a necessary part of constructing a fertilizer warehousing and application model. Literature on machinery cost estimation reveals that descriptive analysis of accounting data, statistical analysis of accounting data, and economic-engineering are the three main approaches used to estimate farm machinery costs. Descriptive and statistical analysis of accounting data entail the use of "real" costs from firms' machinery records to estimate costs whereas an economic-engineering approach uses specific engineering equations and coefficients to estimate the costs.

Estimation of machinery costs using descriptive analysis of accounting data can be accomplished using either a cost accounting or expense accounting method. The cost accounting method expresses capital, material and labor costs in monetary terms regardless of whether or not actual payment is made. The method gives estimates that are useful for comparative purposes. Firms normally use these estimates for comparison with rivals' costs and for strategic analysis and improvement of management. Researchers may use the estimates for the comparison of newly developed mechanization with that of conventional methods.

In contrast to the cost accounting method, the expense accounting method expresses machinery costs in terms of actual payment and expenditure. Therefore, if a subsidy is received or family labor is used, then it is calculated accordingly. While the method provides more realistic estimates, it is not suitable for comparison with machinery costs in other firms or consideration for a long-term improvement in management of the firm. As a result, the cost accounting method is preferred to the expense accounting method (Tsujimoto). This method has been used to study marketing efficiency in the milk industry (Dow).

The cost accounting method is widely used because it is relatively cheap, easy to analyze, realistic, and may provide knowledge to firms on levels of costs and margins. However, record keeping, managerial efficiency, sophistication, and scales of operations are typically not standardized across firms, thus, it is hard to justify the cost comparisons suggested by this approach. Another flaw with this method is that it does not adequately represent costs in terms of broad economic changes and other factors related to the use of machinery (Tembo).

The statistical analysis of accounting data estimates machinery costs through identifying a statistical model, which describes a relationship between a particular machinery cost and a number of explanatory variables such as cumulative aging and inflation. This method uses accounting data obtained from a sample of firms normally for a single period of time. Several studies have used this method. Cross and Perry (1995) used the method to estimate depreciation costs of farm machinery equipment, and Mitchell, Jr. has recently used it to estimate repair cost of construction equipment. Tembo has revealed that the method has also been used in agricultural marketing studies. The major limitation of this method include the "ad hoc" selection of functional forms to estimate machinery costs and the lack of adequate data to construct robust models for estimating the costs (French; Cross and Perry (1995)).

Machinery cost can also be estimated using an economic-engineering approach. The method prescribes a set of guiding principles that have come to be accepted as "standard good practice" (French). The method entails interdisciplinary synthesis of cost functions from detailed specification of output-input relationship. In principle, this is accomplished through consulting relevant firms so as to specify production techniques, estimating the costs, and ultimately synthesizing the cost functions (Middleton and Elam). One advantage of this method over the others is that it can be applied when accounting data are not available. The method is ideal when data cannot reliably be applicable to all scenarios, which might be the case in an industry where operating conditions such as accounting practices, depreciation schedules, cropping patterns, and agronomic practices are firm specific and direct comparisons are illogical (Dahl *et al.*).

In general, the economic-engineering approach is conceptually detailed and is the most preferred. Dumler, Burton, and Kastens compared several machinery depreciation methods and found that when all necessary information needed to estimate machinery costs are not available, the method is the best. However, the approach demands specific technical details, implying high investment cost in research. Also, its application becomes difficult as the size and complexity of the production system increases, and in general, it cannot reasonably account for diseconomies of size (Tembo). To date, the American Society of Agricultural Engineers (ASAE) has developed standard procedures and coefficients useful to estimate machinery costs. This study uses ASAE conventions to estimate costs of fertilizer applicators.

CHAPTER IV

PROCEDURES AND DATA SOURCES

Introduction

The ownership and use of storage facilities and farm machinery entail several variable and fixed costs. Therefore, the relevance of the proposed analytical model depends critically upon availability of reliable cost data and the knowledge of when the costs are incurred. A convenient way to track machinery costs is through careful examination of industry and historic records (Cross and Perry (1996); Lazarus and Selley (2002b)). However, most agribusiness rarely disaggregates cost data into categorical components of fixed and variable costs. Thus, survey design should primarily focus on collecting data useful to estimate variable and fixed costs.

Data Collection

Data used to estimate fertilizer transportation, warehousing, and application costs were collected from different sources. Most of the data were collected during a case study of representative cooperatives located in central Oklahoma, which involved a panel of specialized cooperative staff.

Description of the Studied Cooperatives

Seven cooperatives located in central Oklahoma were studies. The cooperatives are farmer-owned and directly involved in farm supply and grain handling. In summary the cooperatives serve more than 5000 farmers in Canadian, Kingfisher, Blaine, Custer, Dewey, Logan and Oklahoma counties. The locations of cooperatives, which were included in this study, are shown in Figure 2.

● Represents studied cooperatives.

Figure 2 Studied cooperatives in Oklahoma

Data Details

The study elicited detailed information on fertilizer supply chains, shipment costs, and machinery-specific variables such as road and field speed, working widths, horsepower, and list prices. The case study also provided information on warehousing costs and relative demand for different types of fertilizers. Additional data such as appropriate interest and insurance rate, fuel price, and wage rates were obtained from secondary sources, specifically values suggested by similar studies or market surveys (Cross; Dahl, Cobia, and Dooley; Harryman, Siemens, and Kirwan). Data obtained from the case study were compared with contemporary market records and when doubted the information was verified through phone discussions.

In general, the cooperatives had pursued mergers serving nine regions located in different counties of the state. The cooperatives covered a large segment of the Oklahoma fertilizer market, and its business structure more closely reflected a typical multi-location fertilizer firm, which normally demands coordination of business activities. In summary, the data provided estimates required by the mathematical model described below.

The Mathematical Programming Model

The mathematical programming model was developed in a mixed-integer framework to minimize combined costs of transporting, warehousing and applying fertilizers in different forms. The economic rationale behind this choice has been established in chapters two and three. The objective function for the mixed integer-programming model is given as:

(4.1)
$$\text{Min } Z=\sum_{i=1}^{4}\sum_{s=1}^{4}\sum_{w=1}^{7}\beta_{swi}X_{swi}+\sum_{i=1}^{4}\sum_{j=1}^{2}\sum_{w=1}^{7}\sum_{f=1}^{14}\beta_{wfi}X_{wfi}+\sum_{i=1}^{3}\sum_{a=1}^{7}\sum_{f=1}^{14}\beta_{afi}X_{afi}$$
$$+\sum_{i=1}^{3}\sum_{w=1}^{3}\beta_{w}X_{wi}+\sum_{i=1}^{3}\sum_{a=1}^{7}\beta_{a}X_{ai}$$

The objective function is minimized subject to the following constraints:

(4.2) $\sum_{i=1}^{4}\sum_{w=1}^{7}X_{swi}\leq SUP_{si}\quad \forall s=1,2,\ldots,4$ (fertilizer supply constraint)

(4.2) $\sum_{i=1}^{4}\sum_{w=1}^{7}X_{wfi}\geq DEM_{fi}\quad \forall f=1,2,\ldots,14$ (demand constraint)

(4.3) $\sum_{i=1}^{3}\sum_{s=1}^{4}X_{swi}\leq\psi_{w}X_{wi},\ X_{wi}\in\{0,1\},$
$\forall w=1,2,\ldots,7;\ \forall i=1,2,3$ (warehouse storage constraint)

(4.4) $\sum_{i=1}^{3}\sum_{f=1}^{14}X_{afi}\leq\lambda_{a}X_{ai}\quad\forall\ a=1,2,3$ (applicator capacity constraint)

(4.6) $\sum_{i=1}^{4}\sum_{f=1}^{14}X_{wfi}\leq\sum_{i=1}^{4}\sum_{s=1}^{4}X_{swi}\quad\forall w=1,2,\ldots,7$ (fertilizer flow requirement)

(4.7) $X_{ai}\in\{0,1,2,\ldots,n\}$
$\forall\ a=1,2,\ldots,7;\ \forall i=1,2,3$ (integer)

(4.8) $\sum_{i=1}^{3}\sum_{a=1}^{7}X_{afi}=\sum_{i=1}^{3}\sum_{w=1}^{7}X_{wfi}\quad\forall f=1,2,\ldots,14$ (application requirement)

(4.9) $X_{swi},X_{wfi},X_{afi}\geq 0$ (non-negativity condition)

Variables in the programming model are defined as following:

Z	Total cost for the purchase of applicators, warehouse construction, and shipment and application of fertilizers ($).
β_{swi}	Unit transport cost per ton of fertilizer shipped from source *s* to warehouse *w* ($).
β_{wfi}	Unit transport cost per ton of fertilizer shipped from warehouse *w* to field *f* ($).
β_{afi}	Unit application cost per ton of fertilizer type *i* applied at field *f* using applicator *a* ($).
β_{w}	Annual fixed cost associated with building and using a warehouse *w* ($).
β_{a}	Annual fixed cost associated with purchasing and using an applicator *a* ($).
X_{swi}	Quantity of fertilizer type *i* shipped from source *s* to warehouse *w* (tons).

X_{wfi}	Quantity of fertilizer type *i* shipped from warehouse *w* to field *f* (tons).
X_{afi}	Quantity of fertilizer type *i* applied at field *f* using applicator *a* (tons).
X_{ai}	Integer variable for purchasing applicator *a* used to apply fertilizer in form *i*.
X_{wi}	Binary variable for construction of warehouse *w* for storing fertilizer in form *i*, equal to one if construction is feasible, equal to zero otherwise.
DEM_{fi}	Seasonal demand for fertilizer type *i* at field *f* (tons).
SUP_{si}	Supply of fertilizer type *i* at source *s* (tons).
ψ_w	Storage capacity of a warehouse *w* (tons per season).
λ_a	Total material capacity of an applicator *a* per season (tons).

Four versions of the above mathematical model were estimated, one for each of the four fertilizers application systems (model 1 through 4) that are presented in Appendix 1. Details regarding programming, basic assumptions and other details are contained in the detailed models and in the GAMS input codes (Appendix 2). GAMS is a computer program that was used to solve the empirical model and it stands for General Algebraic Modeling System. A verbal description of the four models is provided in chapter four under a section titled estimation of fertilizer demand.

In addition to the specified MIP model, a linear transportation model was also used to identify ideal supply sources when centralized fertilizer storage was prohibited. Choices obtained from this model were useful in comparisons of fertilizer transportation and application costs under centralized and non-centralized arrangements. The comparisons were crucial to assess how quick centralization might be permitted. The transportation model was specified as:

(4.10) $$\text{Min } ZT = \sum_{i=1}^{2}\sum_{s=1}^{2}\sum_{w=1}^{7}\beta_{swi}X_{swi}$$

Subject to:

(4.11) $$\sum_{i=1}^{2}\sum_{w=1}^{7}X_{swi} \leq SUP_{si} \ \forall s = 1, 2, \ldots, 4$$ (fertilizer supply constraint)

(4.12) $$\sum_{i=1}^{2}\sum_{s=1}^{4}X_{swi} \geq CAP_{Wi} \ \forall w = 1, 2, \ldots, 7$$ (storage demand constraint)

In equation 4.10, ZT represents total transportation cost for shipping fertilizers from sources to storage facilities and CAP_{wi} in equation 4.12 stands for fertilizer storage demand at warehouse w. Other variables were defined in the previous model.

The variable and fixed costs described in the above models were estimated using both the data collected from the case study cooperatives and data obtained from historical and market records. Details regarding cost estimation procedures are summarized below.

Estimation of Fertilizer Application Costs

Fertilizer application is associated with several variable and fixed costs of machinery operations. The variable cost is the sum of fuel, oil, repair and maintenance, and labor cost whereas fixed costs include depreciation, interest, and insurance expense. Property tax is typically considered a fixed cost. However, it is not included in most equations based on the assumption that there is no property tax on farm machines (Kastens). Machinery costs used in this study were estimated using the ASAE conventions. The variable cost (VC) and fixed cost (FC) were calculated as:

(4.13) $$VC = C_F + C_O + C_R + C_L + TR_C$$

Where:

C_F =Fuel cost, \$ per acre

C_O =Oil and filter cost, \$ per acre

C_R =Repair and maintenance cost, \$ per acre

C_L =Labor cost, \$ per acre

TR_C =Cost associated with transfer of applicator[6], \$ per acre

(4.14) $$FC = C_D + C_I + C_N$$

Where:

C_D=Depreciation cost, \$ per acre

C_I=Interest cost, \$ per acre

C_N=Insurance cost, \$ per acre

Machinery variable and fixed costs specified above were estimated on a cost-per-acre basis and account for field capacity of machines, which is normally calculated using width and speed of machines, adjusted for field efficiency. Since other variables in the model, such as fertilizer transport cost, are expressed on a cost-per-ton basis, it was necessary to normalize all costs into a per-ton basis. Normalization was done by dividing all the fixed and variable costs by their respective fertilizer application rates measured in tons per acre.

Field efficiency is a measure of field performance of farm equipment and is a ratio between the productivity of a machine under field conditions and the theoretical

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[6] Machinery transfer costs to and from fields are not part of the ASAE specification. The intuition behind the inclusion of this variable is that the proposed model allows machines located in one region to be used in another region, thus incurring substantial machinery transfer costs.

maximum productivity.[7] de Souza, Lima, and Milanez indicate that field performance of a machine is determined by the power of engine, travel speed, drawbar pull, fuel consumption rate, percentage of wheel slip, and temperature of fuel.

Operation inefficiency of farm equipment accounts for factors such as failure to utilize the actual operating width of the machine, idle times, and variations in operating condition of the field (ASAE Standards, 2000). Machinery idle times are mainly attributable to operator's errors, turning the machine, materials handling time, cleaning clogged equipment, and lubrication, adjustments, and refueling of the machine.

Field capacity used to estimate various machinery costs was calculated following the ASAE Agricultural Machinery Management Standard 5.1 mathematically expressed as:

$$F = \frac{S \cdot W \cdot \left(\frac{EF}{100}\right)}{8.25} \tag{4.15}$$

Where:

F = Machinery field capacity, acres per hour
S = Machinery speed, miles per hour
W = Machinery working width, feet
EF = Efficiency factor, percentage

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[7] However, there are many definitions of machinery efficiency. Fulton *et al.* and Mitsui for example have indicated that efficiency in fertilizer application can also be measured through assessment of application accuracy, which is strictly in terms of application rates that are precise and consistent with local soil and crop parameters.

Estimation of Machinery Variable Costs

Machinery variable costs are directly related to hours of use. These costs are relatively simple to quantify because it is possible to get standardized estimates through tracking industry-historical statistics and other relevant market records (Cross and Perry (1996)). Details on estimation of variable costs specified in equation 4.13 are fully discussed below.

Machinery Fuel Cost

Fuel cost was calculated based on after-tax price of diesel and fuel consumption rates for diesel-fueled machinery that was estimated using the ASAE Agricultural Machinery Management Standard 6.3.2.1 shown in equation 4.16 below.

$$C_F = \{P_f \cdot 0.0438 \cdot hp\}\left(\frac{1}{F}\right) \tag{4.16}$$

Where

P_f = Fuel price, \$ per gallon

hp = Maximum PTO horsepower of machine

Machinery Oil Cost

The estimation of cost of engine oil and oil filters was based on the assumption that 100-hours elapsed between oil changes and 200-hours elapsed between oil filter changes. Oil and filter cost (C_O) was estimated using ASAE Agricultural Machinery Management Standard 6.3.3 and was calculated as 15 percent of fuel cost.

$$C_O = 0.15 \cdot C_F \tag{4.17}$$

Machinery Repair Cost

Repair costs accounts for costs incurred in keeping the machine operable from wear, parts failure, and other natural causes of deterioration. Repair costs were calculated based on accumulated hours of use, following ASAE Agricultural Machinery Management Standard 6.3.1 mathematically given as:

$$(4.18) \qquad C_R = \frac{\left(P_m \cdot RF_1 \left(\frac{h+u}{1000} \right)^{RF1} \right) - \left(P_m \cdot RF_1 \left(\frac{h}{1000} \right)^{RF2} \right)}{u} \left(\frac{1}{F} \right)$$

Where:

RF_1 = Repair factor 1

RF_2 = Repair factor 2

u = Use of machine in year n, hours

h = Total accumulated hours of use at beginning of year n, hours

P_m = Price of the machine, dollars

Machinery Labor Cost

Labor cost was calculated using pre-tax wage rate including all payroll benefits (P_L) and machinery labor hours that are estimated based on field capacity of machines. The cost was adjusted using an adjustment factor of 1.25 to account for other labor times such as time used to locate, hook up, and adjust the machines (Cross). Labor cost was estimated as:

$$(4.19) \qquad C_L = \{P_L \cdot 1.25\} \left(\frac{1}{F} \right)$$

Estimation of Applicator Transfer Cost

The analytical model allows fertilizer applicators from a warehouse located in one region to be used in another region. Machinery movement was permitted to assess the feasibility of having machines in central locations so as to maximize annual use thereby reducing machinery costs. Since service regions were several miles apart, the cooperatives would incur extra costs to ship the applicators.

Applicator transfer cost (*ATC*) was calculated as a sum of fuel cost, oil cost, and repair and maintenance cost that would be incurred if applicators were allowed to cross from their locations to other service regions. Actual distances between warehouses where applicators would be placed to fields were estimated using a distance finder at website address http://www.mapblast.com.

Fuel cost (C_{FT}) incurred in shipping an applicator was estimated using round trip travel distances (*Dist*), applicator's fuel consumption rate (FC_{rate}) and after-tax diesel price (P_f) as shown in equation 4.20. Fuel consumption rate in miles per gallon was derived from equation 4.16 and is given in equation 4.21. Oil cost (AO_C) incurred was then calculated as 15 percent of the estimated fuel cost.

$$(4.20) \qquad C_{FT} = \frac{Dist}{FC_{rate}} P_f$$

$$(4.21) \qquad FC_{rate} = 0.73 \cdot 0.06 \cdot hp$$

$$(4.22) \qquad AO_C = 0.15 \cdot C_{FT}$$

Repair and maintenance cost for transferring machines (AR_c) was estimated using round trip travel distance to and from fields, road speed of applicators (*AS*) and a market value of \$ 0.47 per hour traveled, which was inflated from its 1995 equivalence of \$ 0.37 (Dahl *et al.*).[8] Repair and maintenance cost was computed using equation 4.23. The total costs for transferring applicators were divided by adjusted daily material capacities of applicators ($ADMCAP_A$) to get a unit cost per ton of fertilizer applied. The computation formula for the unit costs (*ATC*) is shown in equation 4.24. Details regarding estimation of $ADMCAP_A$ will be discussed later in this chapter.

$$(4.23) \qquad AR_c = 0.47 \cdot \left(\frac{Dist}{AS}\right)$$

$$(4.24) \qquad ATC = \frac{C_{FT} + AO_c + AR_C}{ADMCAP_A}$$

Estimating Fixed Costs of Farm Machinery

Machinery fixed cost (also known as ownership costs) have always been difficult to estimate because understanding machinery ownership costs demands a clear knowledge of how machines are valued over time (Kastens). Cross and Perry (1996) elaborate further that it is difficult to quantify accurately such costs because machinery values are determined based on market transactions whereas budgeting techniques entail valuing a machine without actually selling it. Benston, Mawampanga and Swetnam clarify that machinery fixed costs vary broadly across owners because of differences in repair programs, use intensity, and overall replacement programs. Reid and Bradford show that it is difficult to quantify opportunity costs involved in farm machines because

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[8] Inflation process was achieved through multiplying the ratio of year 2002 to year 1995 industry consumer price indices (CPIs) by the 1995 repair and maintenance value.

of their inter-temporal nature and interdependencies among machinery investment choices, between machinery and production choices, and among production choices.

In general, there have been endless efforts to improve the accuracy of methods currently used to estimate fixed costs of farm machines. Lazarus and Selley (2002b) show that there are many alternative ways to estimate the costs including capital recovery and annuity method suggested by the American Agricultural Economic Association (AAEA) and the ASAE methods. However, the AAEA methods require more detailed data than are available in many business settings.

In view of the data problems discussed earlier in the introductory part of this chapter and the relative strengths and weaknesses of various cost estimation methods detailed in chapter three, machinery ownership costs were calculated using the ASAE methods. Machinery ownership costs are estimated using equations 4.25 through 4.28.

Machinery Depreciation Cost

Annual cost of economic depreciation was calculated as the difference between the dollar value of machine at the beginning of a farming year and the value at the end of the year. Depreciation cost (C_D) was estimated using ASAE Machinery Management Standard 6.1 given in equation 4.26. The remaining value of an applicator at end of year n (RV_n) was calculated as:

$$RV_n = P_m \cdot \left[DF_1 - DF_2\left(n^{0.5}\right) - DF_3\left(u^{0.5}\right)\right]^2 \qquad (4.25)$$

$$C_D = \left(\frac{RV_{n-1} - RV_n}{u}\right)\left(\frac{1}{F}\right) \qquad (4.26)$$

Where

DF_1, DF_2, and DF_3 are depreciation constants suggested by the ASAE.

Machinery Interest Cost

Machinery interest cost is the interest on the capital invested in the machine. Conceptually, interest rate used should reflect conservative rates of return for money that could be obtained in the current market, for example T-bill rate and guaranteed investment contract (GIC) rate are good indicators of the appropriate rate. If capital is in tight supply, then it is ideal to choose a higher rate that gives more return for risky investment (Molenhuis).

The United States Economic Research Service (ERS) for example advocates estimation of machinery interest cost using the capital recovery method, which estimates the cost of replacing the capital investment in machine and equipment that is spent in annual production process plus interest that the remaining capital could have earned in an alternative use. An estimate of the long-run rate of return to farm assets out of current income such as 10-year moving average is recommended as an appropriate rate.

Cross suggests that interest (r) should be estimated as an opportunity cost using the remaining value of machine at the end of the year. This method gives interest cost per acre (C_I) that represents the average cost of capital, which is normally weighted by the source of funds used to finance machines, mathematically expressed as:

$$(4.27) \qquad C_I = \left\{ \frac{r\,RV_n}{u} \right\} \frac{1}{F}$$

In general, there is no consensus on what is the appropriate rate of interest for agricultural investment. Thus, in empirical studies, the choice of interest rate is mostly based on conventions. This study adopted Cross's formula to estimate interest cost for fertilizer applicators using a rate suggested by Langemeier and Taylor. Langemeier and Taylor assumed that machines are replaced after 10-years of use, and investment in machines decreases as the machines depreciate. Based on these two assumptions, they estimated machinery interest cost as a percentage of purchase prices, and they found that, on average, the interest is approximately 5 percent annually.

Insurance Cost

Insurance costs signify risks associated with theft, fire, flood, or other natural disasters. Cross shows that machinery insurance cost is estimated based on initial cost of machine (P_m) and insurance rate (P_i), the former in dollars and the later in percentage. Insurance cost per acre (C_N) is calculated using a formula shown in equation 4.28. Insurance rate adopted in this study is 0.25 percent consistent with the ASAE recommendations.

$$C_N = \left\{\frac{P_m \cdot p_i}{u}\right\}\left(\frac{1}{F}\right) \qquad (4.28)$$

The use of formulae shown in equations 4.15 through 4.28 is typically based on many years of observed engineering estimates. Unfortunately, self-propelled fertilizer applicators are quite new machines and standardized coefficients for efficiency factors, repair factors, and depreciation factors are not available. The absence of these coefficients precludes the use of the ASAE norms. However, it is reasonable to assume that coefficients for fertilizer applicators would be close to that of self-propelled machines such as a combine (Huhnke-personal communication). Thus, combine values summarized in Table 1 are used instead to approximate coefficients for fertilizer applicators.

Table 1 Field efficiency and speed, repair and maintenance, and depreciation factors for self-propelled combine

Field efficiency (EF)		**Field speed (S)**		**Repair Factors**		**Deprecation Factors**		
Typical %	Range %	Typical mph	Range mph	RF1	RF2	DF1	DF2	DF3
70	65-80	3.0	2.0-5.0	0.04*	2.1	1.13*	0.16*	0.01*

* Rounded to two decimal places.
Source: ASAE, 1998.

Estimation of Fertilizer Demand

According to Oklahoma Cooperative Extension Services, crop's demand for nitrogen is calculated based on realistic yield goals. Demand for other primary nutrients are calculated based on soil test values and their corresponding sufficiency levels. Nutrient demands for crops commonly grown in Oklahoma have been calculated and are summarized in OSU Extension Facts No. 2225. The demand for actual nitrogen is two pounds per bushel of wheat up to 50 bushels, above which the demand is slightly greater because the crop's nitrogen use-efficiency decreases.

This study estimated fertilizer demand based on the acreage applied by case-study firm's custom and company's rigs in 2001-2002 wheat production year. Fertilizer tonnage was calculated using two approaches. First, by multiplying the nitrogen and phosphorous application rates for Oklahoma wheat, which are 95 pounds of N and 25 pounds of P_2O_5 per acre by historical acreage data (USDA, 2003). Second, by multiplying the USDA's P_20_5 rate, and the actual nitrogen application rate, which Hossain *et al.* suggest, by the historical acreage data. The first and second approaches represent high and low yield goals, respectively. The second approach was adopted to assess the impacts of decreased nitrogen applications on fertilizer warehousing and application costs.

To meet the specified plant nutrients requirement, there are many fertilizer application options for producers to choose from. Therefore, producers may demand unique mixes of fertilizers based on personal preferences (Stoecker-personal communication). However, such unique demands can only be modeled if preferences are known with certainty. Since field survey was not conducted it was necessary to choose among choices a base-line application system and supportive systems that might replace it when it is shocked by demand or supply factors discussed in the first chapter. The base line-application system is defined as an application system that represents a larger segment of wheat producers in the state or historical practice.

Thus, four possible fertilizer combinations were identified. One possibility for fall application was to apply a blend of diammonium phosphate (DAP), $(NH_4)_2HPO_4$ that has 18-46-0 (N, P_2O_5, and K_2O ratios) and Urea ($(NH_2)_2CO$) with 46-0-0 ratios. Alternatively fall demand could also be met through applying DAP while spring needs are met using urea ammonium nitrate (UAN) with 28-0-0 ratios. These two choices are not very common among Oklahoma farmers who mainly grow dual-purpose wheat that requires several fertilizer applications before harvesting (Epplin-personal communication). Thus, the combinations were included for comparison purposes (i.e. to analyze the extent to which combined costs of satisfying nutrients demands could vary across different combinations of fertilizers. The variation was useful in identifying a least-cost way of satisfying the demand. The incorporation of the DAP and UAN combination in the analysis provided insights to the feasibility of applying very little nitrogen in fall and supplementing the demand through top dressed applications in spring which is highly advocated by agronomists (Gribble).

Another choice was to apply DAP and anhydrous ammonia (82-0-0) during fall followed by UAN in spring. This combination more closely reflects actual practices among Oklahoma's wheat-growers. A final choice was to apply DAP and urea blended together in fall followed by UAN in spring. This option was adopted to assess the likely effects of eliminating anhydrous ammonia in the supply chain following the overall decrease in domestic production and increased role of imported dry fertilizers. Economic reasons for these changes are detailed in the first chapter.

The actual tonnages of fertilizers in each of the four combinations were obtained through multiplying the application rates presented in Table 2 by the locations' total acreages shown in Table 3. The ratios of nitrogen applied during fall and spring were derived from the OSU Agricultural Economics enterprise budgets.

Table 2 Nitrogen and P_20_5 application rates for different combinations of fertilizers

	Application Rates (tons/acre)			
Combination	Anhydrous Ammonia (82-0-0)	Urea (46-0-0)	UAN (28-0-0)	DAP (18-46-0)
DAP, UAN, and anhydrous ammonia (Baseline-case)	0.05[a] 0.03[b]	NA	0.02[a] 0.01[b]	0.03[ab]
DAP, urea, and UAN (Model 2)	NA	0.08[a] 0.06[b]	0.02[a] 0.01[b]	0.03[ab]
DAP and urea (Model 3)	NA	0.09[a] 0.07[b]		0.03[ab]
DAP and UAN (Model 4)	NA	NA	0.15[a] 0.11[b]	0.03[ab]

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[a] Represents application rates based on USDA's fertilize use statistics.

[b] Represents application rates suggested by Hossain *et al.*.

[ab] Represents rates suggested by the USDA and the OSU Agricultural Economics enterprise budget.

NA means not applicable.

Table 3 Total application areas by cooperatives locations

Location	Total Acres
Watonga	17254
Omega	20033
Piedmont	16498
Okarche	45709
Yukon	38299
Kingfisher	53899
Hennessey	18233

Total = 209925 acres.

Source: Mid-Oklahoma Cooperatives.

Estimation of Fertilizer Applicator Capacity

The mathematical model was structured to identify optimal numbers of each type of fertilizer applicator. To facilitate this choice, it was necessary to determine a maximum quantity of fertilizer each of the applicators could apply per season. The quantity is what was referred to as total seasonal material capacity of an applicator in the model description. This variable was calculated using material capacity and effective daily working hours. Material capacity was computed following the ASAE formula presented in equation 4.29.

$$C_m = \frac{S \cdot W . y \left(\frac{EF}{100} \right)}{8.25} \tag{4.29}$$

Where:

C_m =Material capacity, ton per acre

y = Application rate, ton per acre

Other variables were defined in equation 4.15

One way to calculate effective daily working hours of a machine is to adjust potential daily working hours (H_d), defined as maximum number of hours a machine can work in one day, for machinery round trip travel time to and from field (H_t), as well as potential time wastage due to machinery breakdown, also known as machine failure (Epplin-personal communication).

Machine failure is formally defined as the probability of any condition that prevents the operation of the machine or reduces its performance below a specified upper limit. Some of the obvious causes of machine failures are wear, accidents, improper machine operations, and improper scheduling of servicing and maintenance.

In general, the failure (hazard) function and reliability (survivor) function can take any functional form. In practice, lifetime distributions such as exponential, gamma, Weibull and log-normal are widely used to model time to failure (Mygdakos and Gemtos; Parnell, Shaw, and Fritz; Wolstenholme). The adoption of a specific distributional form to describe time to failure depends on the nature of underlying assumptions, problem being addressed and data availability. In the study of farm machines, the exponential form is commonly used (Gruben; Mygdakos and Gemtos; Von Bargen and Peart).

One problem that arises from using the exponential distribution to describe time to failure is the assumption that the rate of failure is constant for the entire life of a machine. This assumption is valid only if all previous failures are addressed before the machine starts its operations and that the machine is replaced at the onset of wear-out period (Shooman). Similarly, evidence from ASAE suggests that breakdown probability of a machine system increases with the increase in farm size.

Therefore, adjustment for breakdown probability followed ASAE formula for accumulated down time and is a function of accumulated hours of use (*u*). The down time (D_t) for diesel-fueled machines was calculated as:

$$D_t = 0.0003234 \cdot u^{1.4173} \qquad (4.30)$$

The breakdown probability (P_b) is total breakdown probability over *m* fields, which was calculated as:

$$P_b = \left(\frac{D_t}{u} \right)^m \qquad (4.31)$$

Total seasonal material capacity of an applicator ($TAMCAP_a$) was estimated using number of days available for field operations per season (ND_a), material capacity (C_m), and effective daily working hours for the machines.

(4.32) $$TAMCAP_a = ND_a \cdot \left[H_d - H_t - P_b \cdot (H_d - H_t)\right] \cdot C_m$$

Estimation of Fertilizer Transport Costs

The proposed programming model includes costs for shipping fertilizers from manufactures or importers to specific warehouse locations and finally to wheat growers. Shipment of fertilizers from sources to warehouses was done using large commercial vehicles whereas company-owned tender trucks were used to ship fertilizers from warehouses to fields. Costs for shipping fertilizers from sources to warehouses were calculated based on commercial freight rates and actual shipment distance. Data on freight rate ($ per ton per mile) were collected during the study and travel distances were calculated using a distance finder at website address specified earlier in the chapter.

Trucking costs for shipping fertilizers between warehouses and fields were calculated based on the assumption that 20-ton tender trucks were used to ship the fertilizers. The costs per ton per mile were calculated using standard values for a 20-ton tender truck, which were 7.5 miles per gallon of fuel, $ 0.05 per mile repair and maintenance cost, and $ 0.03 per mile tires cost (Dahl, Cobia, and Dooley).[9] Therefore, the tender truck cost per ton per mile was $ 0.27.

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[9] The coefficients for repair and maintenance and tire costs were also inflated from their year 1995 values.

Estimation of Warehousing Costs and Storage Capacities

Data regarding warehouse construction costs and storage capacities were collected when the study was conducted. Fixed costs included annual depreciation costs, opportunity costs, maintenance costs, property values and insurance costs. Warehouse annual depreciation costs were calculated using straight-line method expensed over a period of 40 years, which is the life span of concrete/masonry buildings (South Carolina State-Comptroller General's Office). The calculated annual depreciation costs were converted to cost per ton of fertilizer stored using storage capacities of the warehouses.

Opportunity cost of fund spent in construction, annual maintenance of the facilities, and costs associated with property value taxes and insurance were calculated as percentages of warehouse construction values. Warehouse opportunity cost was estimated as 4% of the value, maintenance as 3% of the value, and property value and insurance tax together as 2.5% of the value. Fixed cost for warehousing was calculated as a sum of all these costs.

Data collected during the study are summarized in the GAMS program (Appendix 2).[10] The program is useful for solving different types of mathematical models such as linear and non-linear programming, relaxed mixed integer programming, mixed integer programming, relaxed mixed integer non-linear programming with discontinuous derivatives, and mixed integer nonlinear programming with discontinuous derivatives.

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[10] The mixed integer-programming model was solved using the GAMS CPLEX algorithm.

Description of the Warehousing Structure

The structure of the analytical model also provided a basis for assessing "economies of size" in fertilizer warehousing. To achieve this goal, two warehouse sizes (big and small) for dry and UAN facilities were incorporated in the model. The cooperatives' management determined ideal sizes for warehouses. Big facilities were five times the size of small facilities and were centrally located. The model permitted construction of small warehouses at any location within the business area. Capacities for big facilities were 20,000 tons for dry and 10, 000 tons for UAN. Storage capacity of an anhydrous warehouse was 75 tons (30,000 gallons). The model did not require a central warehouse for anhydrous ammonia because no data on larger size facility was available. Construction costs for dry warehouses were $ 489,990.81 for big facilities and $ 350,000 for small facilities. Construction costs for liquid facilities were $ 1,308,000 for big facility and $ 1,036,800 for small facilities. The cost for anhydrous tank was $ 23,040. Costs for big facilities were $ 1.98/ton for dry, and $ 2.27/ton for UAN. The costs per ton for small facilities were $ 5.67 for dry, $ 6.48 for UAN and $ 7.65 for anhydrous ammonia. In terms of storage cost, big facilities were about 35 percent cheaper on a per ton basis.

Description of Application Equipment

Three different applicators, dry, liquid, and anhydrous were modeled in this study. Dry applicators were used to apply DAP and urea. The working width of dry applicators was 60 feet (Ft), and the field speed was 16.5 miles per hour (mph). Liquid applicators were used to apply UAN, working width and field speed for these applicators were 75 Ft and 19 mph, respectively. The dry and liquid applicators were owned and operated by the case-study cooperatives. The working widths and field speed specified above in conjunction with machinery coefficients provided in Table 1 were used to estimate costs for dry and liquid applicators.

With respect to anhydrous application, two types (big and small) applicators were modeled. The working widths were 20 Ft for small, and 30 Ft for big applicators. The field speed for both applicators was 5 mph, and their efficiency factor (EF) was 80. These applicators were owned by the cooperatives and rented to wheat producers. Therefore, it was difficult to estimate variable costs associated with the use of farmer operated equipment because farmer costs were not known. As a result, this study used $ 5.82 per-acre anhydrous ammonia application cost suggested by Doye, Sahs, and Kletke.

Ownership costs for anhydrous applicators were estimated using secondary data. Depreciation cost used was $ 1.94 per acre (Razarus and Selley). Insurance cost was approximated using purchase price suggested by Langemier and Taylor and machinery hours suggested by Harryman, Siemens, and Kirwan. Interest cost was estimated using purchase price, machinery hours, ASAE formula for computing remaining values of field machines given in equation 4.33 below, and the interest cost formula shown in equation 4.27.

$$(4.33) \qquad RV = 60 \cdot (0.885)^{(n)}$$

Where:

RV = Remaining value as percentage of purchase price at the end of year n

CHAPTER V

RESULTS

This study has addressed four objectives. First, the study has investigated how a shift from anhydrous ammonia towards dry and liquid sources of nitrogen impact on costs of fertilizer warehousing-transportation-delivery systems. Second, the study has compared current fertilizer warehousing and application system for representative cooperatives located in central Oklahoma with the optimal structure evaluated based on coordinated systems and same forms of fertilizer. Third, the study has compared costs between centralized and non-centralized operations for different application systems to assess the feasibility of centralized operation under the warehousing structure that existed in the case study cooperatives. Finally, the study has determined the impact of farm size on the use-efficiency of large-scale machines.

To satisfy these objectives, four models were specified and estimated. The models represented distinct application systems that could be adopted to meet wheat nutrient demands in service regions. The systems permitted combinations of different fertilizers that could be applied in fixed proportions and intervals. Structures of these models are fully described in Appendix 1 and corresponding application rates are provided in Table 2. A common assumption in these models is that fertilizers were applied to provide a total of 95 or 70 pounds of nitrogen and 25 pounds of P_2O_5 per acre. The models were estimated in GAMS software using CPLEX solver.

Impacts of Fertilizer Forms on Firms' Operating Cost

Introduction

The study has used a constant application rate for P_2O_5, and two distinct nitrogen application rates, which correspond to low yield and high yield goals, to model operating costs for the four application systems. The low yield goal rate is used to assess the impacts of decreased demand for nitrogenous fertilizers on the structure and use of warehouses and applicators. This section provides a detailed analysis of operating costs, warehouse structure, and equipment complement for the proposed sets of P_2O_5 and nitrogen application rates. Optimal values obtained using the high yield goal applications are discussed and compared with corresponding values obtained using low yield goal applications.

Costs shown in Table 4 are used to assess extents to which operating costs change from the base-line case. Optimal supply chains summarized in Tables 5 through 8 in conjunction with applicator information contained in Table 9 are used for two purposes. First, to evaluate how the optimal solution for warehouses and equipment complement change from the base-line model. Second, to examine the degree of centralization in fertilizer storage and application.

Table 4 Operating costs for different fertilizer application systems

Model	Costs ($)					
	Fertilizer Transportation (From Sources to Warehouse)	Fertilizer Transportation (From Warehouses to Fields)	Fertilizer Application	Annual Warehousing	Applicator Ownership	Total Cost
Base line-case (Model 1)	166,419.01^{+}	114,913.46^{+}	206,979.95^{+}	269,853.45^{+}	1,181,751.93^{+}	1,939,874.79^{+}
	(0.79)$^{+}$	(0.55)$^{+}$	(0.99)$^{+}$	(1.29)$^{+}$	(5.63)$^{+}$	(9.24)$^{+}$
	131,853.44*	93,729.88*	206,979.95*	273,093.87*	1,181,751.93*	1,887,378.68*
	(0.63)*	(0.45)*	(0.99)*	(1.30)*	(5.63)*	(8.99)*
Model 2	282,592.85^{+}	138,894.11^{+}	206,979.94^{+}	302,128.83^{+}	1,171,352.06^{+}	2,101,947.80^{+}
	(1.35)$^{+}$	(0.66)$^{+}$	(0.99)$^{+}$	(1.44)$^{+}$	(5.58)$^{+}$	(10.01)$^{+}$
	212,303.36*	119,289.20*	206,979.94*	279,448.83*	1,171,352.06*	1,989,373.40*
	(1.01)*	(0.57)*	(0.98)*	(1.33)*	(5.58)*	(9.47)*
Model 3	278,485.39^{+}	145,055.07^{+}	124,003.44^{+}	153,089.26^{+}	552,904.90^{+}	1,253,538.06^{+}
	(1.33)$^{+}$	(0.69)$^{+}$	(0.59)$^{+}$	(0.73)$^{+}$	(2.63)$^{+}$	(5.97)$^{+}$
	207,141.49*	109,449.25*	124,003.44*	153,089.26*	552,904.90*	1,146,588.32*
	(0.98)*	(0.52)*	(0.59)*	(0.73)*	(2.63)*	(5.46)*
Model 4	324,880.19^{+}	226,105.48^{+}	206,979.95^{+}	334,528.83^{+}	1,171,352.06^{+}	2,263,846.51^{+}
	(1.55)$^{+}$	(1.08)$^{+}$	(0.99)$^{+}$	(1.59)$^{+}$	(5.58)	(10.78)$^{+}$
	242,853.31*	168,566.25*	206,979.94*	308,608.834*	1,171,352.06*	2,098,348.07*
	(1.15)*	(0.80)*	(0.98)*	(1.47)*	(5.58)*	(10.00)*

$^{+}$Represents costs for applying 95 pounds of nitrogen and 25 pounds of P_2O_5.

*Represents costs for applying 70 pounds of nitrogen and 25 pounds of P_2O_5.

( ) Represents per acre costs.

Farmers apply anhydrous ammonia. When farmers' cost was included, the application costs for the baseline-model was $ 1,430,774.28 (6.82/acre). The total cost for applying 95 pounds of nitrogen was $ 3,163,712.12 (15.07/acre) whereas the cost of applying 70 pounds was $3,107,962.98 (14.81/acre).

Numbers does not add up exactly due to rounding.

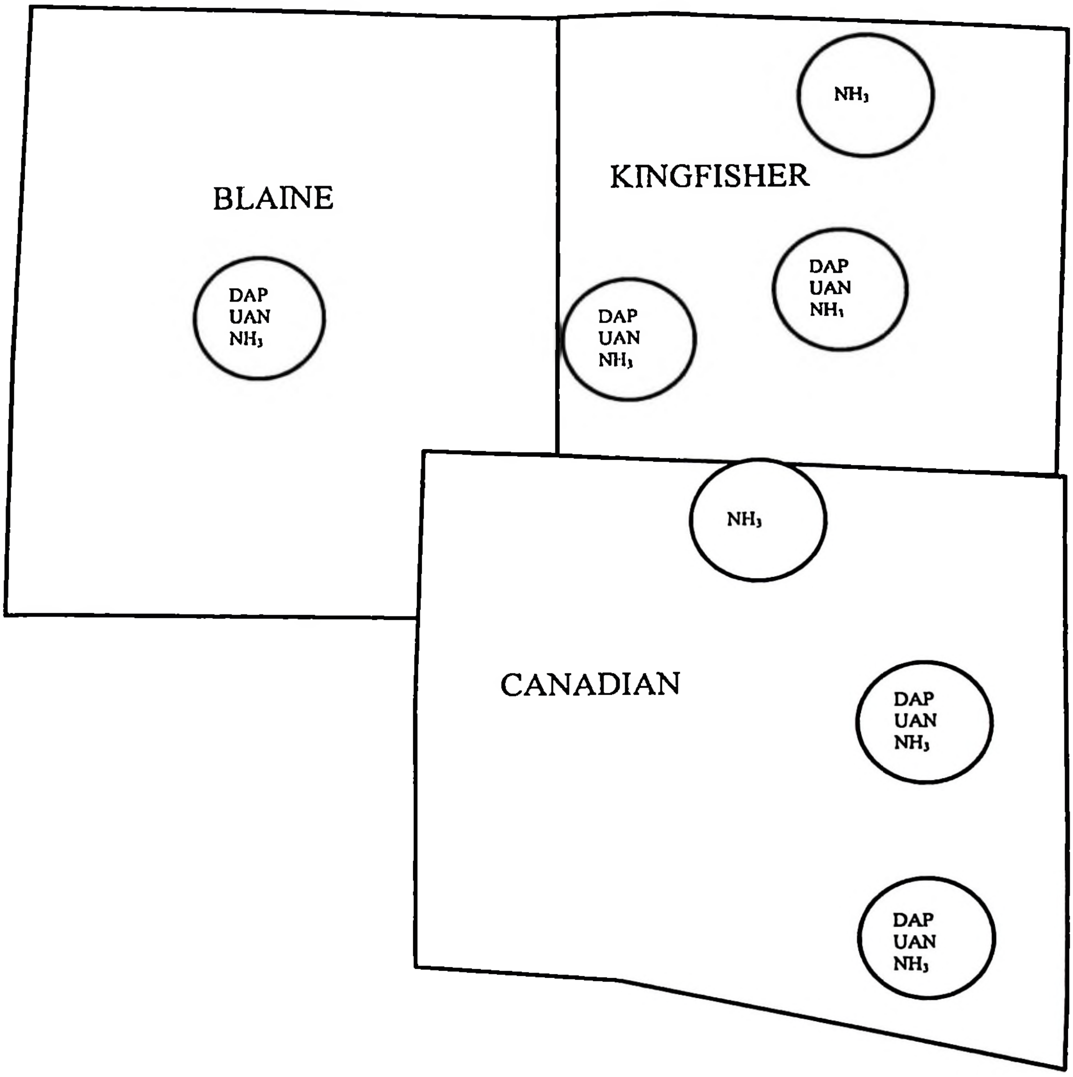
Source: GAMS output.

Table 5 **Optimal supply chains for the baseline model (DAP, NH_3, and UAN)**

Model Description	Fertilizer Type	Source	Warehouse Location	Service Region
Base line-model	DAP	Enid	Kingfisher	Kingfisher, Okarche, and Hennessey
Base line-model	DAP	Enid	Omega	Omega
Base line-model	DAP	Enid	Watonga	Watonga
Base line-model	DAP	Port of Catoosa	Yukon	
Base line-model	DAP	Port of Catoosa	Piedmont	Piedmont
Base line-model	UAN	Enid	Kingfisher	Kingfisher, Okarche, and Hennessey
Base line-model	UAN	Enid	Yukon	Yukon
Base line-model	UAN	Enid	Omega	Omega
Base line-model	UAN	Enid	Piedmont	Piedmont
Base line-model	UAN	Enid	Watonga	Watonga
Base line-model	NH_3	Enid	Kingfisher	Kingfisher
Base line-model	NH_3	Enid	Okarche	Okarche
Base line-model	NH_3	Enid	Yukon	Yukon
Base line-model	NH_3	Enid	Omega	Omega
Base line-model	NH_3	Enid	Piedmont	Piedmont
Base line-model	NH_3	Enid	Hennessey	Hennessey
Base line-model	NH_3	Wood Ward	Watonga	Watonga

NH_3 stands for anhydrous ammonia.
Total number of warehouses: dry = 5, liquid = 5, anhydrous = 7.
Source: GAMS output.

Current warehouse structure: dry = 5, liquid = 9, anhydrous = 9.



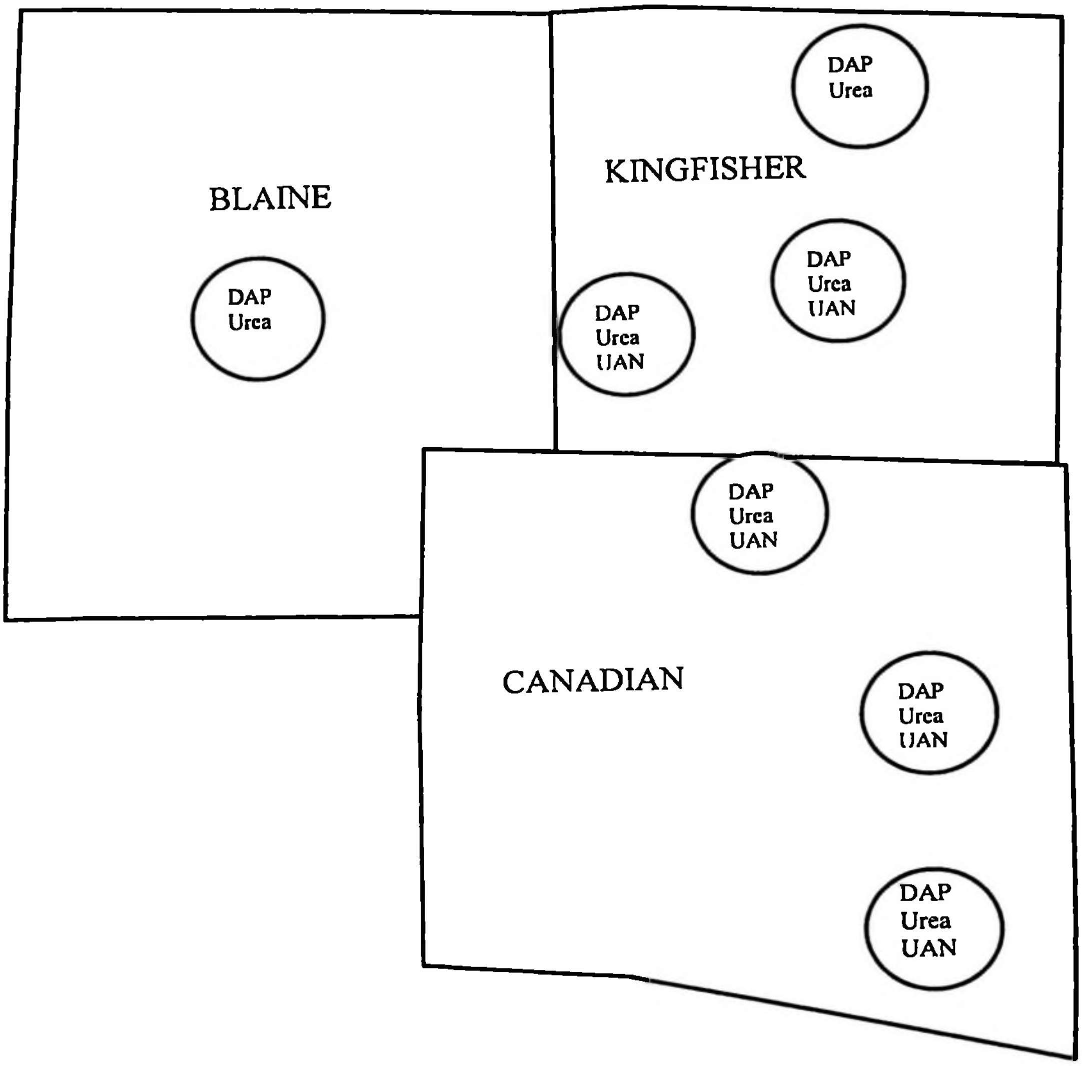
DAP represents DAP facility.
UAN represents UAN facility.
NH3 represents anhydrous ammonia facility.

Figure 3 **Optimal Warehouse Location for the Base-line model**

Table 6 Optimal supply chain for model 2 (DAP, urea, and UAN)

Fertilizer Type	Source	Warehouse Location	Service Region
DAP	Enid	Kingfisher	Kingfisher and Okarche
DAP	Enid	Okarche	Okarche
DAP	Enid	Omega	Omega
DAP	Enid	Watonga	Watonga
DAP	Enid	Hennessey	Hennessey
DAP	Port of Catoosa	Yukon	Yukon
DAP	Port of Catoosa	Piedmont	Piedmont
Urea	Port of Catoosa	Kingfisher	Kingfisher
Urea	Port of Catoosa	Okarche	Okarche
Urea	Port of Catoosa	Yukon	Yukon
Urea	Port of Catoosa	Omega	Omega
Urea	Port of Catoosa	Piedmont	Piedmont and Yukon
Urea	Port of Catoosa	Watonga	Watonga
Urea	Port of Catoosa	Hennessey	Hennessey
UAN	Enid	Kingfisher	Kingfisher, Okarche and Hennessey
UAN	Enid	Yukon	Yukon
UAN	Enid	Omega	Omega
UAN	Enid	Piedmont	Piedmont
UAN	Enid	Watonga	Watonga

Total number of warehouses: dry = 7, liquid = 5.
Source: GAMS output.



Urea represents urea facility.

Figure 4 **Optimal Warehouse Locations for the Second Model**

Table 7 Optimal supply chain for model 3 (DAP and urea)

Fertilizer Type	Source	Warehouse Location	Service Region
DAP	Enid	Kingfisher	Kingfisher and Okarche
DAP	Enid	Omega	Omega
DAP	Enid	Watonga	Watonga
DAP	Enid	Hennessey	Hennessey
DAP	Port of Catoosa	Yukon	Yukon
DAP	Port of Catoosa	Piedmont	Piedmont and Yukon
Urea	Port of Catoosa	Kingfisher	Kingfisher and Okarche
Urea	Port of Catoosa	Yukon	Yukon
Urea	Port of Catoosa	Omega	Omega
Urea	Port of Catoosa	Piedmont	Piedmont
Urea	Port of Catoosa	Watonga	Watonga
Urea	Port of Catoosa	Hennessey	Hennessey

Total number of warehouses = 6.
Source: GAMS output.

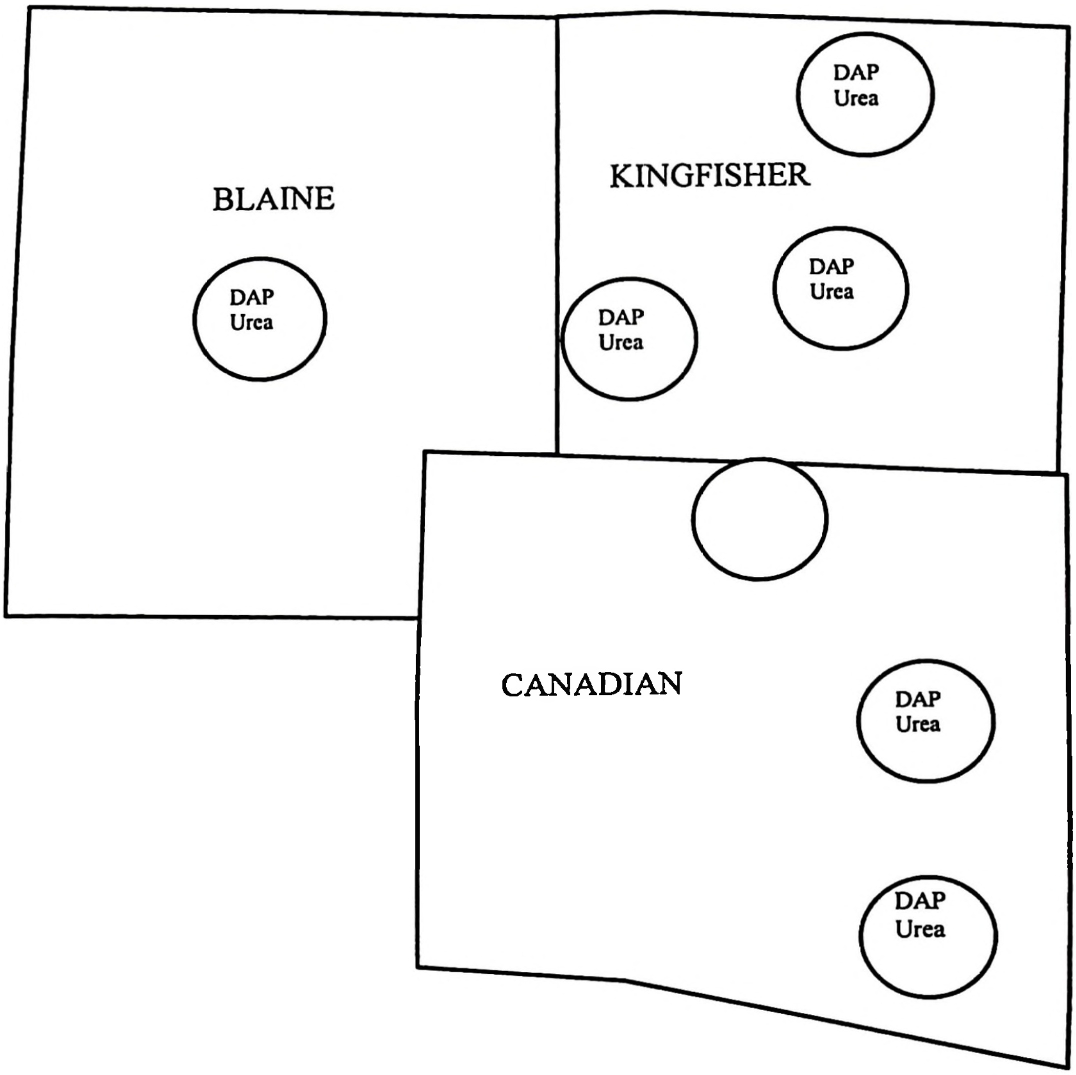


Figure 5 **Optimal Warehouse Locations for the Third Model**

Table 8 **Optimal supply chain for model 4 (DAP and UAN)**

Fertilizer Type	Source	Warehouse Location	Service Region
DAP	Enid	Kingfisher	Kingfisher, Okarche and Hennessey
DAP	Enid	Omega	Omega
DAP	Enid	Watonga	Watonga
DAP	Port of Catoosa	Yukon	Yukon
DAP	Port of Catoosa	Piedmont	Piedmont
UAN	Enid	Kingfisher	Kingfisher, Okarche, and Yukon
UAN	Enid	Okarche	Okarche
UAN	Enid	Yukon	Yukon
UAN	Enid	Omega	Omega
UAN	Enid	Piedmont	Piedmont and Yukon
UAN	Enid	Watonga	Watonga
UAN	Enid	Hennessey	Hennessey

Total number of warehouses: dry =5, liquid = 8 (2 warehouses at Kingfisher).
Source: GAMS output.

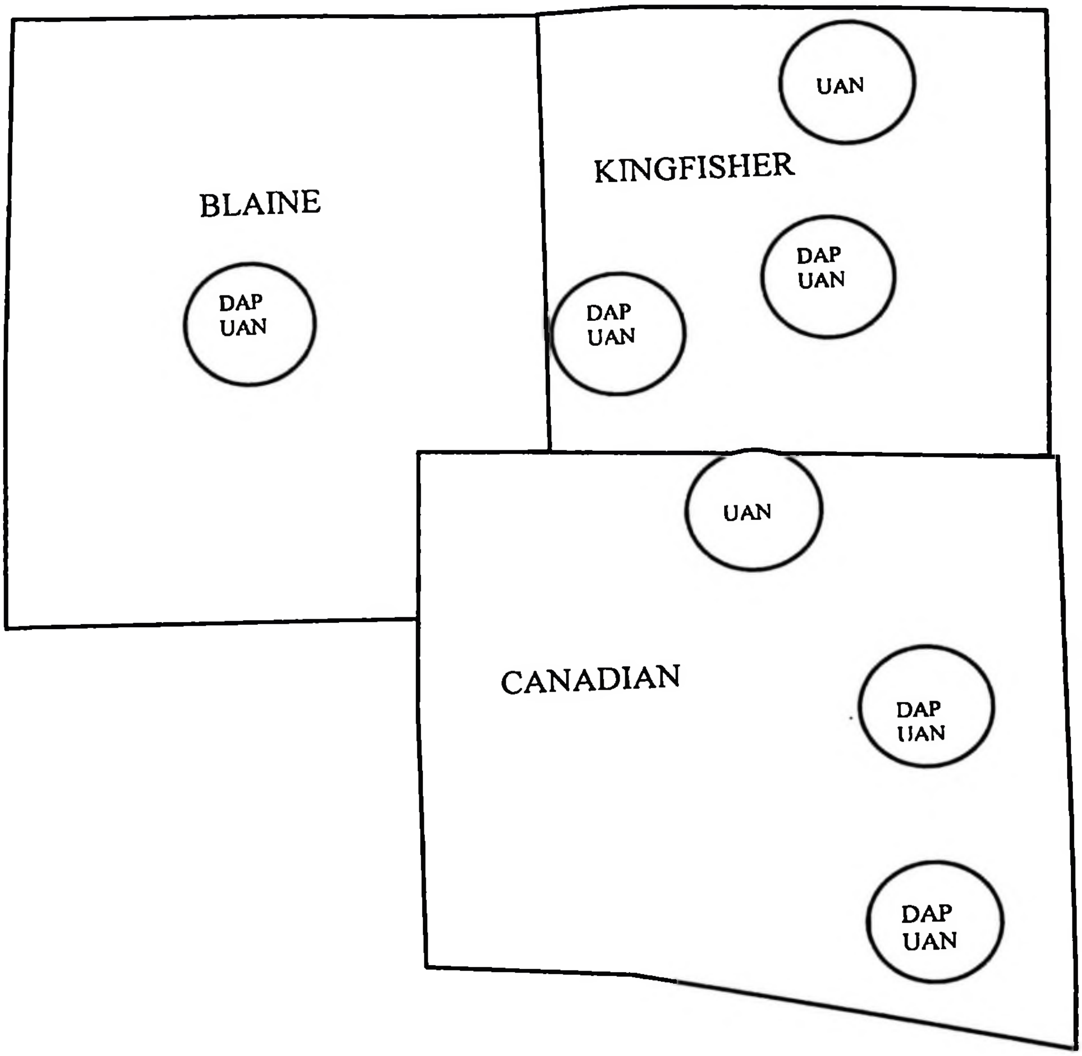


Figure 6 Optimal Warehouse Locations for the Fourth Model

Table 9 Optimal number, location, and use of applicators for different models

Model Description	Applicator Type	Location	Total	Service Areas
Base line-model	Dry	Kingfisher	4	Kingfisher, Okarche, Hennessey, Omega, and Watonga
Base line-model	Dry	Okarche	3	Okarche, Yukon, and Piedmont
Base line-model	Liquid	Kingfisher	6	Kingfisher, Okarche, Hennessey, Omega, and Watonga
Base line-model	Liquid	Okarche	4	Okarche, Yukon, and Piedmont
Base line-model	Anhydrous	Kingfisher	13	Kingfisher
Base line-model	Anhydrous	Okarche	11	Okarche
Base line-model	Anhydrous	Yukon	10	Yukon, and Piedmont
Base line-model	Anhydrous	Omega	5	Omega
Base line-model	Anhydrous	Watonga	5	Watonga
Base line-model	Anhydrous	Piedmont	4	Piedmont
Base line-model	Anhydrous	Hennessey	5	Hennessey
Model 2	Dry	Kingfisher	4	Kingfisher, Okarche, Hennessey, Omega, and Watonga
Model 2	Dry	Okarche	3	Okarche
Model 2	Liquid	Kingfisher	6	Kingfisher, Okarche, Hennessey, Omega, and Watonga
Model 2	Liquid	Okarche	4	Okarche, Yukon, and Piedmont
Model 3	Dry	Kingfisher	4	Kingfisher, Okarche, Hennessey, Omega, and Watonga
Model 3	Dry	Okarche	3	Okarche, Yukon, and Piedmont
Model 4	Dry	Kingfisher	4	Kingfisher, Okarche, Omega, Watonga, and Hennessey
Model 4	Dry	Okarche	3	Okarche, Yukon and Piedmont
Model 4	Liquid	Kingfisher	6	Kingfisher, Okarche, Omega, Watonga, and Hennessey
Model 4	Liquid	Okarche	4	Okarche, Yukon, and Piedmont

Total Applicators: Base line model; dry =7, liquid = 10, anhydrous = 53.
Model 2; dry = 7, liquid = 10. Model 3; dry =7. Model 4; dry = 7, liquid = 10.
Source: GAMS output.
Current number of applicators: dry = 8, liquid = 8, anhydrous = 92.

Table 10 Material and Fertilizer Application Costs for the Modeled Systems

Model Description	Cost $				
	Material	NH_3 Application[1]	Fall Fertilizer Application[2]	Spring Fertilizer Application[2]	Total Cost
Baseline-case (Model 1)	23.66	5.82	3.00	3.00	35.47
Model 2	29.52	NA	3.00	3.00	35.52
Model 3	29.19	NA	3.00		32.19
Model 4	32.06	NA	3.00	3.00	38.06

Fertilizer prices used were $ 300 per ton of NH_3, $ 256 per ton of DAP, $ 240 per ton of urea, and $ 165 per ton of UAN.

[1] Represents estimated Farmers' cost of applying NH_3.

[2] Represents estimated application fee charged by cooperatives.

Source: Own Computation.

Base line-scenario

The first model represented the application of anhydrous ammonium and DAP in fall followed by a "top dressing" application of UAN in spring. Anhydrous ammonium was assumed to be farmer applied with the DAP and UAN applied via the fertilizer supplier's large-scale applicators. This model can be considered the base-line scenario and represents historical application practices.

Using the application rates for high yield goal specified in Table 2, the total cost for the base-line model was $ 1,939,874.79 of which $ 281,332.46 (14.50%) was transportation cost, $ 269,853.45 (13.91%) was warehousing cost, $ 206,979.95 (10.67%) was application cost, and $ 1,181,751.93 (60.92%) was applicator fixed cost. Per acre cost for this base-line case was $ 9.24. The model required five dry warehouses, five UAN warehouse, seven anhydrous warehouses, seven dry applicator, ten UAN applicators, and fifty-three anhydrous applicators.

Table 5 reveals that the base-line model allowed Kingfisher warehouses to store DAP demanded locally and DAP demanded at Okarche and Hennessey. Similarly, the model allowed Kingfisher warehouses to store extra quantities of UAN to satisfy demand at Okarche and Hennessey. As discussed earlier in chapter IV, this model was not designed to allow centralized storage of anhydrous ammonia. With respect to the use of applicators (Table 9), the model permitted only partial centralization of applicators. Dry applicators located at Kingfisher warehouse were also used at Okarche, Hennessey, Omega, and Watonga. Conversely, dry applicators located at Okarche warehouse were also used at Yukon and Piedmont. On the other hand, centralized use of liquid and anhydrous applicators was also observed in this model. The model permitted liquid applicators from Kingfisher to work at Okarche, Hennessey, Omega, and Watonga. Similarly, UAN applicators located at Okarche were also used at Yukon and Piedmont whereas anhydrous applicators located at Yukon were used at Yukon and Piedmont.

Substitution of Urea for Anhydrous Ammonia

The second model involved a combined fall application of DAP and Urea followed by a spring "top dressing" application of UAN. This model represents a likely response to the elimination of anhydrous ammonium. Farmer costs would be expected to be higher than the base-line case because urea is a higher cost source of nitrogen relative to anhydrous ammonia. Total application costs would also be expected to be higher since the firm application of urea is being substituted for farmer application of anhydrous ammonia. Empirical results presented in Table 4 show that total operating costs for the DAP, UAN and urea application system was \$ 162,073.02 higher than that of DAP, UAN and anhydrous ammonia. However, the total cost for the DAP, UAN, and anhydrous ammonia application system excludes \$ 1,223,794.33 farmer's costs of applying anhydrous ammonia.[11]

Detailed analysis showed that the \$ 162,073.02 increase in firms' operating cost when urea was substituted for anhydrous ammonia represented a decrease in applicator ownership cost by \$ 10,399.87, and increases in transportation and warehousing cost by \$ 140,197.51 and \$ 32,275.38, respectively. In terms of per acre cost, the change represents a net increase of \$ 0.77 in firms' cost from \$ 9.24 under the base-line scenario to \$ 10.01 when urea is substituted for anhydrous ammonia. Assessment of results

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[11] Farmers cost for applying anhydrous ammonia include applicator transportation cost from and to the warehouse locations and actual application cost, which is a product of total acreage (209925 acres) and custom rate used in this study (\$ 5.82 per acre).

presented in Tables 5 and 6 show that the optimal number of dry warehouses increased by two whereas the number of UAN warehouses remained constant. Comparison of results given in Table 9 show that the change did not affect the optimal number of dry and UAN applicators.

Existing evidence suggests that anhydrous ammonia has been a least-cost way for producers to satisfy crops' demand for nitrogen (Varsa *et al.*). USDA statistics partly support this conclusion because farm prices averaged over a period of 1995 to 2000 show that the price for N-derived from anhydrous ammonia was $ 0.17 per pound whereas the prices for N-derived from UAN and urea were $ 0.27 and $ 0.25, respectively (USDA, National Agricultural Statistics Service, 2003). Prices for year 2004 are $ 0.71 per pound of N-derived from DAP, $ 0.18 per pound of N-derived from anhydrous, $ 0.29 per pound of N-derived from UAN, and $ 0.26 per pound of N-derived from urea (Mid-Oklahoma Cooperative). Based on year 2004 prices and fertilizer application rate for high yield goal, material cost for the base-line model is $ 23.66 per acre. The material cost increases to $ 29.52 per acre when urea is substituted for anhydrous ammonia. Since, cooperatives charge about $ 3.00 for applying dry or liquid fertilizers, the producers' cost increases from $ 35.48 per acres to $ 35.52 per acre (Table 10). These costs signify that if anhydrous ammonia is completely eliminated in the supply chain then fertilizer-applying firms, as well as wheat growers, might incur extra costs.

Table 6 indicates that the supplies of DAP demanded at Kingfisher and Okarche could be centralized at Kingfisher and supplies of urea demanded at Piedmont and Yukon could be centralized at Piedmont. With respect to centralization of UAN storage, the model permitted Kingfisher warehouse to store extra quantities of DAP to back-up supplies at Okarche and Hennessey. Results in Table 9 show that the model allowed UAN applicators from Kingfisher to apply UAN at Kingfisher, Okarche, Hennessey, Omega, and Watonga. Likewise, the model allowed Okarche applicator's to apply UAN at Okarche, Yukon, and Piedmont. On the other hand dry applicators located at Kingfisher were also used at Okarche, Hennessey, Omega, and Watonga.

Substitution of Urea for Anhydrous Ammonia and UAN

The third model involved application of a blend of urea and DAP in fall. Total application costs for this model would be expected to be lower than other models because the spring "top dressing" application is eliminated. Table 4 reveals that the elimination of UAN and anhydrous ammonia fertilizers from the base-line model decreased total cost by $ 686,336.73. The change represented an increase of $ 142,251.01 in transportation cost, and decreases of $ 82,976.51 in application cost, $ 116,764.20 in warehousing cost, and $ 628,847.04 in applicator ownership cost. According to Tables 5, 7, and 9, the change increased the number of dry warehouses from five to six but did not change the optimal number of dry applicators. In terms of per acre basis the change represented $ 3.27 decrease in operating cost from $ 9.24 under the base-line model to $ 5.97 when urea was substituted for fall applications of anhydrous ammonia and spring applications of UAN. However, material cost per acre would increase from $ 23.66 under the base-line model to $ 29.19 when urea is substituted for both anhydrous ammonia and UAN. Based on costs summarized in Table 10, the net effect of this change is to decrease farmers' cost per acre by $ 3.29 from $ 35.48 to $ 32.19.

However, producers and agribusinesses would have to weigh this cost savings against two factors not addressed in this study. First, some loss of nitrogen occurs due to volatilization between fall and spring, thereby reducing the amount of nitrogen required during the peak growing period in spring. Second, the practice of spring "top dressing" allows producers to evaluate the condition of their wheat crop prior to making full investment in fertilizer. Producers can eliminate or reduce applications to fields that have experienced damage from insects, hail, freeze or other factors.

With respect to the use of warehouses (Table 7), only partial centralization in DAP and urea warehousing was observed. The model allowed warehouses at Kingfisher and Piedmont to store some of the DAP demanded at Okarche and Yukon, respectively. The model also allowed Kingfisher warehouse to store extra quantities of urea to satisfy demand at Okarche. According to results shown in Table 9, this model permitted dry applicators from Kingfisher to apply DAP and urea at Kingfisher, Okarche, Hennessey, Omega, and Watonga. Similarly, Okarche applicators were also used at Yukon and Piedmont.

Substitution of Spring UAN for Fall Anhydrous Ammonia

The fourth model involved an application of DAP in the fall followed by an application of UAN in the spring. This model relates to the latest recommendations of Oklahoma State University agronomists. The basic premise is that fall nitrogen applications based on expected average yield potential are likely to either under estimate or over estimate the nitrogen needs in each particular growing season. Producers are being encouraged to delay nitrogen applications until spring and to make applications (either variable rate or constant rate) based on the crop condition and potential. While the results of this study do not address the possible savings due to variable rate application, they do provide useful information in describing how the costs of warehousing, transportation, and application would be affected by a shift to spring nitrogen application.

Results presented in Table 4 show that a shift from fall application of anhydrous ammonia to spring application of liquid formulations resulted in $ 323,971.73 increase in total cost. The change in cost was attributable to a decrease of $ 10,399.87 in applicator ownership cost and increases of $ 64,675.38 in warehousing cost, and $ 269,696.21 in transportation cost. The shift resulted in $ 10.78 operating cost per acre. Based on results presented in Table 10, this shift increases farmers' cost by $ 2.58 from $ 35.48 under the base-scenario to $ 38.06 when UAN is substituted for fall anhydrous ammonia application. Pair-wise comparisons of results presented in Tables 5 and 8 revealed that the shift increased the number of UAN warehouses from five to eight. Nevertheless, Table 9 shows that the shift did not affect the optimal number of dry and UAN applicators.

Optimal supply chains for DAP and UAN shown in Table 8 indicate that storage of DAP demanded at Kingfisher, Okarche, and Hennessey could be centralized at Kingfisher. The Kingfisher warehouse also stored additional amount of UAN to satisfy demand at Okarche and Yukon. On the other hand, the model allowed Piedmont warehouse to store extra quantities of UAN to meet demand at Yukon.

With respect to the centralization of application equipment, results summarized in Table 9 suggest that Kingfisher applicators' might also be allowed to apply some of the DAP and UAN demanded at Okarche, Omega, Watonga, and Hennessey. Likewise, results show that Okarche applicators' might also be allowed to work at Yukon and Piedmont.

Impacts of Reduced Nitrogen Application Rate on Operating Cost

In general, wheat growers in Oklahoma decide how much nitrogen to apply on wheat based on yield goals. Thus, the actual amount of nitrogen applied differs across geographic regions and fields. Survey results show that on average, dual-purpose wheat growers in Oklahoma might apply about 70 pounds of actual nitrogen per acre (Hossain *et al.*). This section analyses how operating cost changed when nitrogen application rate was reduced from 95 to 70 pounds per acre.

Based on results presented in Table 4, total operating cost for the first model decreased by $ 52,496.11 when nitrogen application rate was reduced from 95 to 70 pounds per acre. The change in the application rate also decreased operating costs for other application systems. The decreases in costs were $ 112,574.40 for the second model, $ 106,949.74 for the third model, and $ 165,498.44 for the fourth model. In terms of per acre costs, the change reduced costs by $ 0.25 for the first model, $ 0.54 for the second model, $ 0.51 for the third model, and $ 0.79 for the fourth model. These changes in costs were attributable to decreases in fertilizer transportation and annual warehousing costs. Table 11 summarizes optimal numbers of warehouses and applicators for the two application rates.

Table 11 Comparison of optimal numbers of warehouses and applicators for applying 95 and 70 pounds of actual nitrogen

	Total Number of Warehouses		Total Number of Applicators	
Model Description	95 Pounds of N	70 Pounds of N	95 Pounds of N	70 Pounds of N
Base line-case (Model 1)	5[a]	5[a]	7[a]	7[a]
	5[b]	5[b]	10[b]	10[b]
	7[c]	7[c]	53[c]	53[c]
Model 2	7[a]	6[a]	7[a]	7[a]
	5[b]	5[b]	10[b]	10[b]
Model 3	6[a]	6[a]	7[a]	7[a]
Model 4	5[a]	5[a]	7[a]	7[a]
	8[b]	7[b]	10[b]	10[b]

NB: [a] Stands for dry warehouses or applicators.
[b] Stands for liquid warehouses or applicators.
[c] Stands for anhydrous warehouses or applicators.

Source: GAMS output.

The reason for the decrease in transportation cost is that the quantity of nitrogenous fertilizers shipped from sources to warehouses and finally to fields, decreases as the application rate falls. On the other hand, the decrease in annual warehousing cost was also expected because storage demand decreases as the application rate falls. This change was reflected in the second and the fourth models, where the total number of warehouses decreased by one. Applicator ownership costs did not change when the N rate was decreased because the optimal number of applicators does not depend on the application rate.

Impact of Changes in Machinery Working Days on Firms' Costs

Fertilizer application is one of the "time sensitive" activities because it is highly influenced by weather. Historical weather patterns normally play an important role to determine optimal levels of farm machinery. Therefore, a sensitivity analysis was done to assess extents to which changes in weather impacted on the operating costs of the fertilizer-applying firms. This analysis was based on the 25 pounds of P_2O_5 and 95 pounds of actual nitrogen and it accounted for possible increases and decreases in machinery working days in fall and spring.

The "looping procedure" in the GAMS software was used to analyze the impacts of increased and reduced machinery hours on firms' operating costs and equipment complement. Results obtained from the sensitivity analysis are presented and discussed next.

Table 12 Impact of increased machinery hours on firms' total cost ($)

Model Description	Base	25% Increase	33% Increase
	Scenario		
Base-line case	1,939,874.79 (9.24)	1,610,785.32 (7.67)	1,469.455.62 (7.00)
Model 1	2,101,947.80 (10.01)	1,824,093.97 (8.69)	1,759,687.78 (8.38)
Model 2	1,253,538.06 (5.97)	1,174,184.53 (5.59)	1,174,184.53 (5.59)
Model 4	2,263,846.51 (10.78)	2,070,185.57 (9.86)	1,944,192.94 (9.26)

Source: GAMS Output.

Table 13 Impact of reduced machinery hours on firms' total costs ($)

Model Description	Scenario Base	 25% Decrease	 33% Decrease
Base-line case	1,939,874.79 (9.24)	2,144,574.32 (10.22)	2,543,946.53 (12.12)
Model 2	2,101,947.80 (10.01)	2,304,852.67 (10.98)	2,689,2683.51 (12.81)
Model 3	1,253,538.06 (5.97)	1,332,508.06 (6.35)	1,493,106.11 (7.11)
Model 4	2,263,846.51 (10.78)	2,466,478.58 (11.75)	2,748,296.50 (13.09)

Source: GAMS Output.

Table 14 Impact of increased machinery hours on equipment complement

	Scenario		
Model Description	**Base**	**25% increase**	**33% Increase**
Base-line case	7[a] 10[b] 53[c]	6[a] 8[b] 42[c]	5[a] 7[b] 40[c]
Model 1	7[a] 10[b]	6[a] 8[b]	6[a] 7[b]
Model 2	7[a]	6[a]	6[a]
Model 4	7[a] 10[b]	6[a] 8[b]	6[a] 7[b]

[a] Stands for dry applicators.
[b] Stands for liquid applicators.
[c] Stands for anhydrous applicators.
Source: GAMS Output.

Table 15 Impact of decreased machinery hours on equipment complement

Model Description	Scenario Base	 25% Decrease	 33% Decrease
Base-line case	7[a]	10[a]	10[a]
	10[b]	12[b]	15[b]
	53[c]	70[c]	80[c]
Model 1	7[a]	9[a]	10[a]
	10[b]	13[b]	15[b]
Model 2	7[a]	9[a]	10[a]
Model 4	7[a]	10[a]	10[a]
	10[b]	15[b]	15[b]

Source: GAMS Output.

Sensitivity results presented in Tables 12 and 13 reveal that operating costs as well as per acre costs for the modeled fertilizer application systems decreased and increased when machinery working days were increased and decreased, respectively. Generally, when the application period is prolonged, fertilizer-applying firms might need only a small number of machines because they might schedule applications sequentially across service regions. In contrast, when the application period is short, it becomes difficult for machines located in one area to work in other areas. As a result, firms might require a relatively large number of machines.

Results in Tables 14 and 15 show the impacts of changes in machinery hours on equipment complement. The impact of changes in machinery hours on equipment complement was evaluated at 25% and 33%. Results indicated that the number of applicators changed less drastically when machinery hours were increased than when decreased. Based on the scenario evaluations, it seems logical for fertilizer-applying firms to have a "sufficient number" applicators to contend with weather risk that might reduce machinery hours in fall and spring seasons.

Summary

The foregone discussion has provided details regarding operating costs for different application systems and corresponding changes in warehousing and application equipment. Using the 25 pounds of P_20_5 and 95 pound of actual nitrogen as application rates, the combined cost for the DAP, anhydrous ammonia, and UAN application system was \$ 9.24 per acre. The costs per acre for other application systems at these application rates were \$ 10.01 for the DAP, UAN, and urea, \$ 5.97 for the DAP and urea, and \$

10.78 for the DAP and UAN. However, the cost per acre decreased when the nitrogen rate was reduced to 70 pounds. The decreases were \$ 0.27 for base-line model, \$ 0.54 for the second model, \$ 0.51 for the third model, and \$ 0.79 for the fourth model. Operating costs for these application systems are given in Table 4.

Scenario analysis was conducted to assess the impact of increased and decreased machinery hours on operating costs and equipment complement. The analysis indicated that the optimal number of applicators decreased when fertilizer application period was long and increased when the period was short. Consequently, operating costs were low when the period was long and high when the period was short. However, the changes in costs were relatively less dramatic for increased machinery hours. This analysis suggests that it is important for fertilizer-applying firms to contend with weather risks that might reduce machinery hours.

Overall, centralization in warehousing and applications observed in all models were either between regions in the same neighborhood or zones. In all four models, no single case allowed a complete centralization of warehousing or application activities. A detailed discussion of warehouse structure and number of applicators for the modeled application systems is provided below.

Briefly, warehousing and application costs accounted for over 12% of the total cost. Tables 5 through 9 summarize how these components of the optimal supply chains varied with fertilizer forms. Comparison of results displayed in Tables 5 and 6 show that the number of dry warehouses increased when urea was substituted for anhydrous ammonia. Also results in Tables 6 and 7 indicate that the number of dry warehouses increased when urea was substituted for both anhydrous ammonia and UAN. Similarly, results in Tables 5 and 8 indicate that the number of UAN warehouses increased when the UAN was substituted for anhydrous ammonia. Nonetheless, the optimal number of dry warehouses was unchanged when UAN was substituted for both anhydrous ammonia and urea because DAP demand was the same for both model 1 and model 4. The increases in warehouses were justifiable because the storage demand was high when the quantities of dry and liquid fertilizers were increased in supply chains.

Based on applicator statistics presented in Table 9 the number of dry applicators did not change across models because dry fertilizers are normally blended when applied. Thus, the increase in the quantity of dry fertilizers applied only changed the application rate and not the number of applicators. Similarly, the number of liquid applicators did not change across models.

Comparison of Base-line Model with Current Structure

This section examines how the optimal number of warehouses and applicators under the base-line model relates to current warehousing and application equipment. Tables 5 and 9 also provide a summary of the case study cooperatives' current warehouse infrastructure and complement of application equipment, respectively. Comparing this structure with the model results provides a qualitative assessment of efficiency of the current system of fertilizer transportation, application, and warehousing. The results suggest that the firm is operating its application equipment near its theoretical capacity. However, the current network of liquid warehouses is relatively more extensive than the system suggested by the models' optimal supply chains.

The optimal warehouse number for the base-line model was 17 i.e. five dry warehouses, five liquid warehouse, and seven anhydrous warehouses. Currently, the cooperatives have five dry warehouses, nine liquid warehouses, and nine anhydrous warehouses. Thus, the current system has more warehouses than what would be needed under partial centralized storage. This decrease in warehouse number elaborates likely efficiency gain when the existing warehouses are replaced with large-scale warehouses.

However, with respect to the optimal number of applicators, the base-line model requires seven dry applicators, ten liquid applicators, and fifty-three anhydrous applicators whereas, under the current system, there are eight dry, eight liquid, and ninety anhydrous applicators. The increase in number of liquid applicators under the modeled system partly reflects difficulties in coordinating machinery movement.

One explanation for the high number of anhydrous applicators in the current structure is the current complement of small-scale equipment rented to farmers for direct application. The capabilities of small-scale machines were not considered in the analysis due to difficulties in estimating the actual acreage or their utilization. On the other hand, the scenario evaluation results presented earlier in this chapter indicated that the base-line model was sensitive to changes in machinery hours. Thus, another explanation for the high number of anhydrous applicator is probably to accommodate peak demand, which might arise due to unpredictable weather changes. The decrease in number of anhydrous applicators in the base-line model may also indicate some inefficiency in coordination of anhydrous equipment under the current system.

Costs under Partially Centralized and Non-centralized Systems

Models used in this study were constructed to represent costs that would be incurred if capacities of warehouses and application equipment would change to allow centralized warehousing and application. Since the objective was to assess whether it is feasible for the studied cooperatives to opt for partial or complete centralization, it was necessary to compare operating costs under centralized and non-centralized arrangements. However, two difficulties were encountered.

One of the difficulties was that under centralized warehousing and application, supply sources were endogenously identified, which translates that the choice of storage facilities would not necessarily be the same if centralization was prohibited. However, one would expect that cooperative managers are rational and they process all information to examine costs for all alternatives sources before ordering purchases. Therefore, when comparisons were made supply sources were selected using a linear transportation model shown in equations 4.10 through 4.12.

Another difficulty was that warehousing costs under centralized and non-centralized arrangements were completely different. While the models assumed that cooperatives would invest substantially in new warehouse construction or analogously expansion of storage capacities, the costs of existing warehouses were fixed and irrelevant to the decision. Because direct comparison of warehousing costs would be misleading, only transportation, application and equipment ownership costs were included in the comparisons. The identified cost difference in transportation, application, and equipment ownership could be considered by the agribusinesses and compared with the economies of size in warehouse construction. Results for these comparisons are shown in Table 16.

Table 16 **Comparison of transportation, application and equipment ownership costs for partially centralized and non-centralized business operations**

Model Description	**Costs ($)** **Partial-Centralization**	**Non-Centralized**
Base-line model	1,670,064.31	1,849,129.65
	(7.96)	(8.81)
Model 2	1,799,818.97	2,136,563.19
	(8.57)	(10.18)
Model 3	1,100,448.80	1,345,424.42
	(5.24)	(6.41)
Model 4	1,929,317.68	2,311,713.82
	(9.19)	(11.01)

Source: Own Computation.

Results indicated that partial centralization would decrease combined costs of fertilizer transportation and application, and equipment ownership. The decreases were $ 179,065.34 (0.85/acre) for the baseline-model, $ 336,744.22 (1.61/acre) for the second model, $ 244,975.62 (1.17/acre) for the third model, and $ 382,396.14 (1.82/acre) for the fourth model. The observed cost-savings were attributable to the benefits of economies of size in warehousing and enhanced capacity utilization of the machines under partially centralized arrangement.

However, there is always a tradeoff between cost savings that arise from economies of size in warehousing and increased transportation cost. In general, centralization raises transportation costs because materials must first be transported to central warehouse and then to final destinations. Nonetheless, economies of size, is always apparent in large-scale warehousing. Dahl, Cobia, and Dooley conducted a study in North Dakota and found that warehousing cost per ton decreased as the size of the facility increased. On the other hand, capacity utilization of farm machines normally increases when the area of operation increases. Consequently, allowing machines from one area to work in areas that are in close proximity increase their use-efficiency.

The analysis of the results presented in this section was based on the assumption that the warehousing structure would change to allow large-scale storage. Therefore, given the scale of business and storage capacities that existed in the studied cooperatives, it is unlikely that cooperatives will invest in centralized warehouses while the existing warehouses are in usable condition. However, as the warehouse structures become obsolete, cooperatives may adopt centralized warehousing and machinery operations to serve adjacent demand areas.

Furthermore, centralized warehousing suggested in this study is product-specific. Thus, it is likely for fertilizers that are applied together (e.g. DAP and urea) to be stored in distant warehouses thereby increasing material shipping time and cost. A similar but more complex situation might also arise when fertilizers are stored in different locations and equipments are located in a warehouse different from fertilizer storage locations. In such events, synchronization of fertilizer supplies and machinery movements become very crucial.

In brief, there are machinery-capacity utilization and vehicle scheduling problems that come with centralized warehousing. First, centralization may result into substantial ineffectiveness in satisfying application demands, especially when the demands arise simultaneously and transportation resources are scarce. Therefore, routing the delivery of fertilizers to meet application needs at all demand points represents a major operational challenge to the cooperative management. Second, demand points are located in different areas. Thus, any failure to coordinate the delivery of fertilizers and machinery movement could potentially reduce machinery-working hours, thereby reducing its capacity utilization.

Feasibility of a Single Central Storage Facility

Sensitivity evaluations were used to assess the feasibility of having a single storage facility for fertilizers. The evaluation process was achieved through iterative reduction of annual warehousing costs for the big facilities. These reductions reflected increased economies of size for large warehouses. However, single warehousing never came into the optimal solution. To illustrate the cost differential of a single warehouse, the models were constrained to single large-scale dry and liquid warehouses. The cost disadvantage of a central warehouse relative to the optimal solutions is provided in Table 17 below.

Table 17 The impact of single coordinated warehouse on operating cost

Model	Costs ($)			
	Change in Fertilizer Transportation (From Sources to Warehouse)	Change in Fertilizer Transportation (From Warehouses to Fields)	Change in Applicator Ownership Cost	Net Impact on Transportation and Application Cost
Model 2	-11,159.6 -(0.05)	+354,953.54 +(1.69)	+78,986.42 +(0.38)	+422,780.32 +(2.01)
Model 3	-6,035.24 -(0.03)	+321,600.83 +(1.53)	+78,986.41 +(0.38)	+394,552.00 +(1.88)
Model 4	-60,898.40 (0.29)	+472,432.41 +(2.25)	+157,972.83 +(0.75)	+569,506.84 +(2.71)

The application rates used in this analysis are 95 pounds of N and 25 pounds of P_20_5.

- Represents decrease in cost.

+ Represents increase in cost.

The baseline-model is excluded from this analysis because data on large-scale storage of anhydrous ammonia was not available.

Source: GAMS output.

Results presented in Table 17 show that the adoption of a single coordinated warehousing for dry and liquid fertilizers would increase operating costs and the number of applicators. The increases in costs were $ 422,780.32 ($ 2.01/acre) for the second model, $ 394,552.00 ($ 1.88/acre) for the third model, and $ 569,506.84 ($ 2.71/acre) for the fourth model. These increases in costs offset the financial gains from economies of size in warehousing, which are $ 239,760.00 ($1.14/acre) for the second model, $ 113,400.00 ($ 0.54/acre) for the third model, and $ 272,160.00 ($ 1.30/acre) for the fourth model. In summary, this analysis indicates that in the supply and application of fertilizers, fertilizer transportation and applicator ownership and fleet costs have much impact than warehousing cost. Detailed analysis has revealed that some of the service regions were as far as 56 miles apart, allowing machines to travel that far would reduce machinery hours by approximately 28 percent thereby increasing machinery costs. Despite the increased costs that come with centralized systems, there are also management advantages in coordinated systems. These advantages are discussed below.

Management Advantages of a Single Location Warehousing

The cost analysis of centralized warehousing used in this study does not address management and human resource issues, also known as X-efficiency.[12] A single location warehouse system could reduce the number of production and management personnel relative to multi-location systems. The system could also improve the coordination of equipment. Additionally, a centralized warehouse designed to receive unit train (110 car) rail shipments could also experience significant advantages in transportation costs.

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[12] X-efficiency is broadly defined as improvement in the use of human resources (e.g. through training and motivation or incentive programs).

Empirical evidence suggests that rail grain rates differ by market, commodity, and shipment size. There is a consistent rate savings in shipping via larger-car trains. While the exact limits vary by rail carrier, trains in the 100 to 110-car range usually represent the maximum size for a train. The unit-car rate reflects the saving in loading/unloading, switching, and waiting time that the rail carriers experience when they do not have to consolidate grain cars with other users in assembling an optimal length train (Kenkel, Henneberry, and Augustini). The unit train rates reflect 30% (approximately $ 3.30/ton) cost advantage for fertilizer transportation.

The previously discussed cost disadvantages for a centralized warehouse translate to approximately $ 16/ton for all three models. Taken alone, unit-train rail rate savings are likely to be insufficient to justify a single centralized warehouse. However, the combined synergy in management, labor efficiency and rail transportation should be considered in assessing the cost advantages and disadvantages of a single location warehousing.

Efficiency Differential for Using Applicators in Big and Small Fields

Another objective of this study was to compare relative efficiency of using fertilizer applicators in big and small fields.[13] Understanding the impact of farm size on warehouse and application costs will help agribusinesses to assess how the current trends in size will impact their future supply structures. Field size cost information would also help cooperatives to analyze the benefits of coordinating applications across fields and the likelihood of differential pricing for big and small producers.

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[13] The definition of large and small fields is arbitrary. Large field are defined as fields that are over 110 acres where as small fields are less than 60 acres.

This objective was evaluated using optimal values obtained from the GAMS output through comparing total time lost when applicators move between fields. The basic assumption is that in absence of coordinated use of the machines, the applicators would move between fields more frequently when used in small fields than when used in big fields. This assumption may not be realistic because it is possible to coordinate applications between big and small fields. However, the assumption is adopted to completely separate the use of machines in big and small fields.

Moreover, under centralized application, the comparison is meaningful only when applicators do not move from one region to another region. Applicators might appear to be inefficient when allowed to move between regions simply because travel times reduce machinery hours. The tradeoff between dollar savings emanating from reduced operating costs and ineffectiveness that arises from difficulty in coordinating operations across service regions is a common phenomenon in most centralized systems. While it is possible to achieve efficiency through reducing overall costs, the achievement may undermine local effectiveness as centralization leads to increased customer services and geographic coverage. The GAMS output summarized in Table 9, revealed extensive coordination of machinery use across regions. Thus, when the comparisons were made, machinery movements across regions were prohibited. Results for these comparisons are summarized in Table 18.

Table 18 Machinery use-efficiency evaluated based on travel hours per day

		Big Field		Small Field	
Applicator Type	**Machinery Hours**	**Travel Hours**	**Efficiency (%)**	**Travel Hours**	**Efficiency (%)**
Dry	10	1.25	87.50	3.00	70.00
Liquid	10	1.38	80.00	3.75	62.50

Source: Own calculation based on machinery field capacity, travel speed, and total acres.

Results reveal that both the dry and the liquid applicators were about 17.5% more efficient when used in large fields. Overall, the liquid applicators were relatively less efficient than dry applicators because they had higher field speed and longer working width. Therefore, the liquid applicators could apply fertilizers faster than the dry applicators. Consequently, the liquid applicators moved between fields more frequently than the dry applicators. A pattern that emerged from this qualitative analysis is that as machinery capacity increases it becomes less efficient when used in small fields.

Percentage-wise the differences in machinery use-efficiency were small. However, these numbers are critically dependent on relative proportions of large and small fields as well as actual sizes of fields. In general, farm size offers some advantage in reducing machinery costs. However, such advantage becomes large when the farm size is greater than 800 acres. Schnitkey for example, observed that machinery cost for 180-490 acre farm was only 6 percent higher than a farm of 500-799 acres.

Farm supply agribusinesses, particularly those organized as farmer-owned cooperatives are frequently interested in determining if there are cost differences in meeting the needs of small versus large producers. The cost difference is important in determining pricing strategies. Results suggest that the variation of application costs with farm size is more likely related to difficulties in coordinating the use of applicators across service regions than with the actual field efficiency.

The cost impact of the observed machinery use-inefficiency might become significant as the number of machines increases. Since the U.S. Agriculture is highly dynamic, as the structure of farming business changes and field sizes continue to increase the difference might become significant in the future and it might be important for fertilizer applying firms to examine the feasibility of coordinating application activities or charging producers based on their field sizes.

CHAPTER VI

SUMMARY AND CONCLUSIONS

The difficulty to control cost in a dynamic industry where competitiveness and costs are changing over time has long been recognized. More recently, fertilizer suppliers in the U.S. have been striving to keep pace with the changes in business environment. The changes arise from growing global competition, increased regulations in the industry for environmental and safety concerns, and changing demand. These changes have raised marketing costs of fertilizer supply and application firms.

This study has developed a comprehensive framework, which is used to compare current fertilizer warehousing and application for cooperatives located in central Oklahoma with the optimal structure evaluated based on coordinated operations and same forms of fertilizer. The framework is also used to determine the impact of farm size on use-efficiency of large-scale machines. Additionally, the proposed framework is used to track the likely effects of eliminating anhydrous ammonia in the supply chain as its production trend continues to decline, and a shift from dry and anhydrous applications in fall towards spring application of liquid formulations. Scenario evaluations were incorporated in the analyses to assess the impacts of changes in machinery hours on costs and equipment complement. Also the sensitivity analysis was used to assess the feasibility a single location warehousing.

The analytical framework was formulated based on the concept of supply chain management. This framework was adopted because in the fertilizer industry consolidation of materials in warehouses and centralization of application equipment has emerged as an effective cost-saving method due to high percentage of total distribution or costs associated with transportation and fixed-asset charges.

In brief, when 95 pounds of N and 25 pounds of P_2O_5 were applied on wheat, the cost for DAP, UAN and anhydrous ammonia application system was approximately $ 9.24 per acre. The cost for DAP, UAN and urea was about $ 10.01 per acre and the costs for DAP and urea, and DAP and UAN application systems were $ 5.97 and $ 10.78, respectively. When the nitrogen application rate was reduced to 70 pounds, the costs decreased slightly. The costs per acre were $ 8.99 for the DAP, UAN and anhydrous ammonia, $ 9.47 for the DAP, UAN and urea based system, $ 5.46 for the DAP and urea system, and $ 9.99 for the DAP and UAN application system.

At the 95 pounds of N and 25 pounds of P_2O_5 application rates, a shift from anhydrous ammonia to urea will increase cooperatives' operating cost by $ 0.77/acre (approximately 8%). Additionally, dry and liquid formulations of nitrogen fertilizers are more expensive as measured by cost per actual unit of nitrogen. At current prices shifting to urea-based system (model 2) would increase material cost by $ 5.86 /acre (almost 25%) at the nitrogen and P_2O_5 rates used in this study. Farmers' cost of applying fertilizers would decrease by $ 5.82/acre (49.24%) from $ 11.82/acre under the baseline-model to $ 6.00/acre when urea is substituted for anhydrous ammonia. Therefore, this shift signifies an increase of $ 0.04/acre (0.11%) in farmers' cost.

Shifting to fall-only urea system (model 3) would decrease cooperatives' cost by $ 3.27/acre (approximately 35%). Nevertheless, fertilizer material cost would increase by $ 5.53/acre or 23.37%. Therefore, farmers' application costs would decrease by $ 8.82/acre (74.62%) from $ 11.82/acre under the baseline-model to $ 3.00/acre. The net effect of this change is to decrease farmers' cost by $ 3.29/acre (9.27%). However, this gain must be weighted against potential nitrogen loss due to volatilization and cost for fertilizer applied to crops that might be damaged by pests or bad weather.

Transition to fall application of DAP and spring application of UAN (model 4) would increase cooperatives' cost by $ 1.54 /acre (about 16.67%). The transition would also increase material cost by $ 8.40/acre (approximately 36%). Farmers' cost of applying fertilizers would decrease by $ 5.82 (49.24%) from $ 11.82/acre to $ 6.00/acre. Overall, this change would increase farmers' cost by $ 2.58 per acre. In spite of the fact that the total cost increases when UAN is substituted for anhydrous ammonia, it is unrealistic to speculate the effect of this change on wheat producers because nitrogen needs and utilization at specific stage of wheat growth are not fully understood. Bly and Winther have indicated that nitrogen application rate and the timing of application influence grain protein and yield in hard red winter wheat. Therefore, even with the constant N rate, it is reasonable to assume that the timing of application might influence wheat yield. Therefore, the impact of substituting UAN for anhydrous ammonia on wheat producers is subject to further investigation.

Scenario evaluations indicated that costs per acre as well as the optimal number of applicators for the modeled fertilizer systems decreased when machinery hours were increased, and increased when the hours were decreased. The evaluations indicated that the number of applicators changed slightly when machinery hours were increased than when decreased. Based on these evaluations, it seems logical for fertilizer-applying firms to have "a sufficient" number of applicators to contend with weather risks that might reduce machinery hours in fall and spring seasons.

The comparison of optimal supply chain results with the current warehousing and application system indicated that the case study firm was operating its dry and liquid applicator fleet near its theoretical capacity. The current structure appears to have excess capacity in anhydrous applicators, which probably reflects the difficulties in coordinating fleet or farmer-applied equipment, and a need for excessive capacity to accommodate peak demand that might arise due to unpredictable weather changes. The current structure also appears to have excess warehouses.

Analysis of efficiency differential for using applicators in small and big fields was based on comparisons of times lost when applicators moved between fields. The basic assumption for this analysis was that in absence of coordinated use of machines, the applicators would move between fields more frequently when used in small fields than when used in big fields. The assumption was adopted to completely separate the use of machines in small and big fields. Results revealed that both the dry and liquid applicators were 17.8% more efficient when used in big fields. However, liquid applicators were relatively less efficient than dry applicators because they had higher field capacity. A pattern that emerged from this qualitative analysis is that as machinery capacity increases it becomes less efficient when used in small fields.

In summary the efficiency differential is small. However, as the structure of farming business changes and field sizes continue to increase the difference might become notable in the future. Thus, it might be important for fertilizer applying firms at that time to examine the feasibility of coordinating applications across adjacent fields or charging producers based on their field sizes.

In general, this study has identified that storage structures currently existing in cooperatives' businesses are not big enough to offer sufficient economies of size to offset transport costs across the geographically dispersed service regions. Thus, it is unlikely that centralized warehousing and application can be afforded in the near future. However, as the warehousing structure becomes obsolete, it might be possible to adopt partial centralized fertilizer storage and application across adjacent regions when new warehouses are constructed.

Total system coordination is not feasible because some of the locations are very far from each other and moving machines to such locations reduce machinery hours by approximately 28%. Similarly, service regions are geographically dispersed and far from each other, as a result high transportation costs offset financial gains from economies of size in warehousing.

The centralizations, which emerged in this study, impose some planning difficulty. Based on empirical results, it is possible for fertilizers that are applied together (e.g. DAP and urea) to be stored in distant warehouses thereby increasing material shipping time and cost. A similar, but more complex situation might also arise when fertilizers are stored in different locations and applicators are located in a warehouse different from fertilizer storage locations. In such events, synchronization of fertilizers supplies and machinery movements becomes very important. Furthermore, weather variability is always anticipated in farm operations and it is difficult to assess timeliness costs with simple programming models.

Despite the fact that results supported partial centralization, the choices were critically influenced by the modeling assumptions and partly by cost coefficients, which were estimated using general principals (cost estimation methods).

Additionally, there are other problems that come with centralization. In supply systems that entail centralized warehousing, flexibility is very limited because storage capacities are fixed. Therefore, even small disturbances in consumer demand may alter cost functions across the supply chain. In fertilizer business, such changes might arise from two phenomena. First, as domestic production of anhydrous ammonia continue to decrease and the role of imported dry fertilizers increases, fluctuations in global supply will greatly impact demand for warehousing and storage efficiency. One way to avert the supply shocks is to have excess storage, which may suggest allowing subjective flexibility in determining optimal storage capacities. Second, there has been continuing efforts to increase efficiency and accuracy of fertilizer application methods. Techniques that can identify more accurately fertilizer application rates are becoming popular and application rates are continuously being reviewed. For example, research results from long-term experiment, conducted at Lahoma indicate that actual amounts of nitrogenous fertilizers required for maximum wheat yield vary from year to year (Gribble; Johnson *et al.*). Clearly, the extents to which changes in global production and fertilizer application rates will affect demand are unpredictable and are subject to further investigation.

Another challenge is that peak seasons for fertilizer application occur during a short period and may be much shorter when weather variability is envisaged. Since a tradeoff between machinery waiting times and working hours is likely, unless it is possible to load multiple tender trucks at a time, then the problem of queuing at central warehouses is likely. Thus, proper vehicle routing might be crucial to reduce queuing.

Nevertheless, the disadvantages of centralized storage and coordinated use of applicators discussed above, need to be compared with economies of size in warehousing, benefits from enhanced X-efficiency, and potential gains from coordinated use of applicator and rail transportation.

Specific Conclusions

i) The operating cost of fertilizer-supplying firms might increase by \$ 0.77 and \$ 1.54 per acre when urea and UAN are substituted for anhydrous ammonia, respectively. However, the cost might decrease by \$ 3.27 per acre when urea is substituted for both anhydrous ammonia and UAN.

ii) With respect to farmers' cost, the substitution of urea and UAN for anhydrous ammonia might increase the cost by \$ 0.04 and \$ 2.58 per acre, respectively. Farmers' cost might decrease by \$ 3.29 per acre when urea is substituted for anhydrous ammonia and UAN.

iii) The existing warehouse structure has more warehouses than the structure evaluated based on coordinated storage. The management might consider the adoption of partially centralized storage system to serve adjacent demand points when new warehouses are constructed.

iv) The analysis has indicated that the studied cooperatives operate dry and liquid applicators near their optimal capacities. Nevertheless, the cooperatives have excess capacity in anhydrous ammonia applicators.

v) It is not cost-effective to totally centralize fertilizer storage and application activities because demand points are geographically dispersed and far from each other.

vi) Analysis of machinery-use efficiency has indicated that both dry and liquid applicators were about 18% more efficient when used in large fields than in small fields. The analysis also indicated that as the machinery capacity increases it becomes less efficient when used in small fields. These results could justify differential pricing of application services.

Limitations and Suggestions for Further Research

This study has provided a comprehensive model for assessing the feasibility of centralized fertilizer warehousing and application. The model has accounted for down times that arise from failure and machinery movements, as well as differences in operating costs across different fertilizer combinations and farm sizes. While the analytical framework is relevant, the validity of empirical results is highly influenced by correctness of cost coefficients used. However, most of the cost coefficients were estimated using industry data, historical records or cost estimation procedures suggested by the ASAE. Thus, estimated costs may differ from real-business costs.

Fertilizer applicators' costs are probably weak than warehousing costs because they were estimated based on the assumption that coefficients for self-propelled combine would be close representatives. On the other hand, warehousing costs would be more accurate if they were calculated using averaged budgets from construction firms.

In addition to data quality problem, the analysis itself was static in nature. Data used in this study represented transactions under merger. Since the cooperatives had just merged at the time data were collected, time series for fertilizer demand was not available. Therefore, inferences may not capture variations in fertilizer demand.

In terms of future research, it would be interesting to apply the proposed framework to re-estimate costs when coefficients for fertilizer applicators and warehouse construction budgets become available. Variations in demand could probably be accounted for if stochastic demand models were used.[14] The analytical models could also be improved to accommodate scheduling of machinery movement across service regions based on working days probabilities, relative demand for application and travel distance.

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[14] A stochastic demand model uses probabilities to estimate a demand for a particular product or good. The model is robust in the sense that it captures variation of the demand across time.

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APPENDICES

APPENDIX 1
DETAIL DESCRIPTION OF MATHEMATICAL MODELS

Models Assumptions

i) Fertilizers in all service regions are supplied through cooperative system. Thus, the models assume no inter-firm competition in fertilizer supply.

ii) Demand at farm-level is represented by fields that are evenly distributed in space about five miles from warehouse locations and the flow of materials from warehouses to fields follow shortest routes.

iii) The models assume that the cooperative management would carefully design work schedules for machinery to avoid weather effects that might limit field machine operations.

iv) The models assume constant fertilizer application rates across all service regions. Therefore, no adjustments were made in the application rates to account for variations in nitrogen and phosphate contents in soils.

v) The models assume climate and weather patterns are similar across service regions, i.e. fertilizers were applied during the same periods.

vi) No spatial differences in operating costs (i.e. fuel prices, wage rates, and other machinery and warehousing costs were identical across regions).

vii) The business does not incur storage cost for farm machinery.

viii) The business allocates resources to minimize aggregate costs of fertilizer transportation, warehousing, and application.

ix) No fertilizer quality difference across suppliers. This assumptions means that fertilizers from different sources are perfect substitutes.

x) No carry over in storage is permitted. Warehouse should be big enough to store fertilizers demanded in one season only.

xi) Fertilizer supply is limited but big enough to satisfy demand. This assumption ensures that the choices of supply sources are strictly based on differences in transportation costs.

xii) Applicators are freely to move across service regions.

Model 1

$$\begin{aligned}\text{Min } Z_1 = {} & \sum_{s=1}^{2}\sum_{w=1}^{7} Q_{sw}^{DAP}\beta_{sw}^{DAP} + \sum_{s}\sum_{w=1}^{7} Q_{sw}^{UAN}\beta_{sw}^{UAN} + \sum_{s=1}^{2}\sum_{w=1}^{7} Q_{sw}^{Anh}\beta_{sw}^{Anh} + \sum_{w=1}^{7}\sum_{f=1}^{14} Q_{wf}^{DAP}\alpha_{wf}^{DAP} \\ & + \sum_{w=1}^{7}\sum_{f=1}^{14} Q_{wf}^{UAN}\alpha_{wf}^{UAN} + \sum_{w=1}^{7}\sum_{f=1}^{14} Q_{wf}^{Anh}\alpha_{wf}^{Anh} + \sum_{a=1}^{7}\sum_{f=1}^{14} Q_{fa}^{DAP}\psi_{fa}^{DAP} + \sum_{a=1}^{7}\sum_{f=1}^{14} Q_{fa}^{UAN}\psi_{fa}^{UAN} \\ & + \sum_{a=1}^{14}\sum_{f=1}^{14} Q_{fa}^{Anh}\psi_{fa}^{Anh} + \sum_{a=1}^{7}\lambda_a^{DAP}X_a^{DAP} + \sum_{a=1}^{7}\lambda_a^{UAN}X_a^{UAN} + \sum_{a=1}^{7}\lambda_a^{Anh}X_a^{Anh} \\ & + \sum_{w=1}^{7}\phi_w^{DAP}X_w^{DAP} + \sum_{w=1}^{7}\phi_w^{UAN}X_w^{UAN} + \sum_{w=1}^{7}\phi_w^{Anh}X_w^{Anh}\end{aligned}$$

Subject to:

$\sum_{w=1}^{7} Q_{sw}^{DAP} \le Q_s^{DAP} \quad \forall s$ (DAP supply constraint)

$\sum_{w=1}^{7} Q_{sw}^{UAN} \le Q_s^{UAN} \quad \forall s$ (UAN supply constraint)

$\sum_{w=1}^{7} Q_{sw}^{Anh} \le Q_s^{Anh} \quad \forall s$ (anhydrous ammonia supply constraint)

$\sum_{w=1}^{7} Q_{wf}^{DAP} \ge Q_f^{DAP} \quad \forall f$ (satisfy DAP demand)

$\sum_{w=1}^{7} Q_{wf}^{UAN} \ge Q_f^{UAN} \quad \forall f$ (satisfy UAN demand)

$\sum_{w=1}^{7} Q_{wf}^{Anh} \ge Q_f^{Anh} \quad \forall f$ (satisfy anhydrous ammonia demand)

$\sum_{f=1}^{14} Q_{wf}^{DAP} = \sum_{s=1} Q_{sw}^{DAP} \quad \forall w$ (balanced DAP flow)

$\sum_{f=1}^{14} Q_{wf}^{Liq} = \sum_{s=3} Q_{sw}^{UAN} \quad \forall w$ (balanced UAN flow)

$\sum_{f=1}^{14} Q_{wf}^{Anh} = \sum_{s=4} Q_{sw}^{Anh} \quad \forall w$ (balanced anhydrous ammonia flow)

$$\sum_{s=1} Q_{sw}^{DAP} \leq X_{w}^{DAP} \cdot CAP_{w}^{DAP} \ \forall w$$

(storage constraint for DAP fertilizers)

$$\sum_{s=3} Q_{sw}^{UAN} \leq X_{w}^{UAN} \cdot CAP_{w}^{UAN}$$

(storage constraint for UAN)

$$\sum_{s=4} Q_{sw}^{Anh} \leq X_{w}^{Anh} \cdot CAP_{w}^{Anh} \ \forall w$$

(storage constraint for anhydrous fertilizer)

$$\sum_{f=1}^{14} Q_{fa}^{DAP} \leq X_{a}^{DAP} \cdot CAP_{a}^{DAP} \ \forall a$$

(DAP applicator capacity constraint)

$$\sum_{f=1}^{14} Q_{fa}^{UAN} \leq X_{a}^{UAN} \cdot CAP_{a}^{UAN} \ \forall a$$

(UAN applicator capacity constraint)

$$\sum_{f=1}^{14} Q_{fa}^{Anh} \leq X_{a}^{Anh} \cdot CAP_{a}^{Anh} \ \forall a$$

(anhydrous applicator capacity constraint)

$$\sum_{w=1}^{7} Q_{wf}^{DAP} = \sum_{a=1}^{7} Q_{fa}^{DAP} \ \forall f$$

(application requirement for DAP fertilizers)

$$\sum_{w=1}^{7} Q_{wf}^{Liq} = \sum_{a=1}^{7} Q_{fa}^{UAN} \ \forall f$$

(application requirement for liquid fertilizers)

$$\sum_{w=1}^{7} Q_{wf}^{Anh} = \sum_{a=1}^{7} Q_{fa}^{Anh} \ \forall f$$

(application requirement for anhydrous fertilizers)

$$Q_{sw}^{DAP}, Q_{sw}^{UAN}, Q_{sw}^{Anh}, Q_{wf}^{DAP}, Q_{wf}^{UAN}, \\ Q_{wf}^{Anh}, Q_{fa}^{DAP}, Q_{fa}^{UAN}, Q_{fa}^{Anh} \geq 0$$

(non-negativity condition)

$$X_{a}^{DAP},\ X_{a}^{UAN},\ X_{a}^{Anh} \in \{0, 1, 2, \ldots, n\}$$

(integer solution for machinery selection)

$$X_{w}^{DAP}, X_{w}^{UAN}, X_{w}^{Anh} \in \{0,1\} \\ \forall\, w = 1, 2, \ldots, 7$$

(binary variables for warehouse construction)

Variables in model 1 are defined below:

Z_1 is total cost for shipping, warehousing, and applying fertilizers.

Q_{sw}^{DAP} is quantity of DAP shipped from sources to warehouses (tons).

β_{sw}^{DAP} is cost for shipping DAP from sources to warehouses ($ per ton).

Q_{sw}^{UAN} is quantity of UAN shipped from sources to warehouses (tons).

β_{sw}^{UAN} is cost for shipping UAN from sources to warehouses ($ per ton).

Q_{sw}^{Anh} is quantity of anhydrous ammonia shipped from sources to warehouses (tons).

β_{sw}^{Anh} is cost for shipping anhydrous ammonia from sources to warehouses ($ per ton).

Q_{wf}^{DAP} is quantity of DAP shipped from warehouses to fields (tons).

α_{wf}^{DAP} is cost for shipping DAP from warehouses to fields ($ per ton).

Q_{wf}^{UAN} is quantity of UAN shipped from warehouses to fields (tons).

α_{wf}^{UAN} is cost for shipping UAN from warehouses to fields ($ per ton).

Q_{wf}^{Anh} is quantity of anhydrous ammonia shipped from warehouses to fields (tons).

α_{wf}^{Anh} is cost for shipping anhydrous ammonia from warehouses to fields ($ per ton).

Q_{fa}^{DAP} is quantity of DAP applied at field *f* using applicator *a* (tons).

ψ_{fa}^{DAP} is cost for applying DAP at farm *f* using applicator *a* ($ per ton).

Q_{fa}^{UAN} is quantity of UAN applied at field *f* using applicator *a* (tons).

ψ_{fa}^{UAN} is cost for applying UAN at field *f* using applicator *a* ($ per ton).

Q_{fa}^{Anh} is quantity of anhydrous ammonia applied at field *f* using applicator *a* (tons).

ψ_{fa}^{Anh} is cost for applying anhydrous ammonia at field *f* using applicator *a* ($ per ton).

λ_{a}^{DAP} is fixed costs associated with the use of DAP applicators ($ per ton).

λ_a^{UAN} is fixed costs associated with the use of UAN applicators ($ per ton).

λ_a^{Anh} is fixed costs associated with the use of anhydrous applicators ($ per ton).

ϕ_w^{DAP} is fixed cost of owning DAP warehouses ($ per year).

ϕ_w^{UAN} is fixed cost of owning UAN warehouses ($ per year).

ϕ_w^{Anh} is fixed cost of owning anhydrous ammonia warehouses ($ per year).

Q_s^{DAP} is quantities of DAP supplied by manufacturers or importers (tons).

Q_s^{UAN} is quantities of UAN supplied by manufacturers or importers (tons).

Q_s^{Anh} is quantities of anhydrous ammonia supplied by manufacturers or importers (tons).

Q_f^{DAP} is total demand for DAP (tons).

Q_f^{UAN} is total demand for UAN (tons).

Q_f^{Anh} is total demand for anhydrous ammonia (tons).

CAP_w^{DAP} is storage capacities of DAP warehouses (tons).

CAP_w^{UAN} is storage capacities of UAN warehouses (tons).

CAP_w^{Anh} is storage capacities of anhydrous warehouses (tons).

CAP_a^{DAP} is seasonal material capacities of DAP applicators (tons).

CAP_a^{UAN} is seasonal material capacities of UAN applicators (tons).

CAP_a^{Anh} is seasonal material capacities of anhydrous ammonia applicators (tons).

Model 2

$$\begin{aligned}\text{Min } Z_2 = {} & \sum_{s=1}^{2}\sum_{w=1}^{7} Q_{sw}^{DAP}\beta_{sw}^{DAP} + \sum_{s}\sum_{w=1}^{7} Q_{sw}^{Urea}\beta_{sw}^{Urea} + \sum_{s}\sum_{w=1}^{7} Q_{sw}^{UAN}\beta_{sw}^{UAN} + \sum_{w=1}^{7}\sum_{f=1}^{14} Q_{wf}^{DAP}\alpha_{wf}^{DAP} \\ & + \sum_{w=1}^{7}\sum_{f=1}^{14} Q_{wf}^{Urea}\alpha_{wf}^{Urea} + \sum_{w=1}^{7}\sum_{f=1}^{14} Q_{wf}^{UAN}\alpha_{wf}^{UAN} + \sum_{a=1}^{7}\sum_{f=1}^{14} Q_{fa}^{Dry}\psi_{fa}^{Dry} + \sum_{a=1}^{7}\sum_{f=1}^{14} Q_{fa}^{UAN}\psi_{fa}^{UAN} \\ & + \sum_{a=1}^{7}\lambda_a^{Dry}X_a^{Dry} + \sum_{a=1}^{7}\lambda_a^{UAN}X_a^{UAN} + \sum_{w=1}^{7}\phi_w^{Dry}X_w^{Dry} + \sum_{w=1}^{7}\phi_w^{UAN}X_w^{UAN}\end{aligned}$$

Subject to:

$$\sum_{w=1}^{7} Q_{sw}^{DAP} \le Q_s^{DAP} \quad \forall s \qquad \text{(DAP supply constraint)}$$

$$\sum_{w=1}^{7} Q_{sw}^{Urea} \le Q_s^{Urea} \quad \forall s \qquad \text{(urea supply constraint)}$$

$$\sum_{w=1}^{7} Q_{sw}^{UAN} \le Q_s^{UAN} \quad \forall s \qquad \text{(UAN supply constraint)}$$

$$\sum_{w=1}^{7} Q_{wf}^{DAP} \ge Q_f^{DAP} \quad \forall f \qquad \text{(satisfy DAP demand)}$$

$$\sum_{w=1}^{7} Q_{wf}^{Urea} \ge Q_f^{Urea} \quad \forall f \qquad \text{(satisfy urea demand)}$$

$$\sum_{w=1}^{7} Q_{wf}^{UAN} \ge Q_f^{UAN} \quad \forall f \qquad \text{(satisfy UAN demand)}$$

$$\sum_{f=1}^{14} Q_{wf}^{DAP} = \sum_{s=1} Q_{sw}^{DAP} \quad \forall w \qquad \text{(balanced DAP flow)}$$

$$\sum_{f=1}^{14} Q_{wf}^{Urea} = \sum_{s=2} Q_{sw}^{Urea} \quad \forall w \qquad \text{(balanced urea flow).}$$

$$\sum_{f=1}^{14} Q_{wf}^{UAN} = \sum_{s=3} Q_{sw}^{UAN} \quad \forall w \qquad \text{(balanced UAN flow)}$$

$$\sum_{s=1} Q_{sw}^{DAP} + \sum_{s=2} Q_{sw}^{Urea} \le X_w^{Dry}\cdot CAP_w^{Dry} \quad \forall w \qquad \text{(storage constraint for dry fertilizers)}$$

$\sum_{s=3} Q^{Liq}_{sw} \le X^{Liq}_{w} \cdot CAP^{Liq}_{w} \ \forall w$ (storage constraint for liquid fertilizer)

$\sum_{f=1}^{14} Q^{Dry}_{fa} \le X^{Dry}_{a} \cdot CAP^{Dry}_{a} \ \forall a$ (dry applicator capacity constraint)

$\sum_{f=1}^{14} Q^{UAN}_{fa} \le X^{UAN}_{a} \cdot CAP^{UAN}_{a} \ \forall a$ (UAN applicator capacity constraint)

$\sum_{w=1}^{7} Q^{DAP}_{wf} + \sum_{w=1}^{7} Q^{Urea}_{wf} = \sum_{a=1}^{7} Q^{Dry}_{fa} \ \forall f$ (dry fertilizers application requirement)

$\sum_{w=1}^{7} Q^{UAN}_{wf} = \sum_{a=1}^{7} Q^{UAN}_{fa} \ \forall f$ (UAN application requirement)

$Q^{DAP}_{sw}, Q^{Urea}_{sw}, Q^{UAN}_{sw}, Q^{DAP}_{wf}, Q^{Urea}_{wf}$
$Q^{UAN}_{wf}, Q^{Dry}_{fa}, Q^{UAN}_{fa} \ge 0$ (non-negativity condition)

$X^{Dry}_{a},\ X^{UAN}_{a} \in \{0, 1, 2, \ldots, n\}$ (integer solution for machinery selection)

$X^{Dry}_{w},\ X^{UAN}_{w} \in \{0, 1\} \forall a = 1, 2, \ldots, 7$ (binary variables for warehouse construction)

Most of the variables included in model 2 are defined in the first model, definitions for other variables are provided below.

Z_2 is total cost for shipping, warehousing, and applying fertilizers.

Q^{Urea}_{sw} is quantity of urea shipped from sources to warehouses (tons).

β^{Urea}_{sw} is cost for shipping urea from sources to warehouses ($ per ton).

Q^{Urea}_{wf} is quantity of urea shipped from warehouses to fields.

α^{Urea}_{wf} is cost for shipping urea from warehouses to fields ($ per ton).

α_{wf}^{Urea} is cost for shipping urea from warehouses to fields ($ per ton).

Q_{fa}^{Dry} is quantity of DAP and urea applied at field f using applicator a (tons).

ψ_{fa}^{Dry} is unit cost for applying DAP and urea at field f using applicator a ($ per ton).

λ_{a}^{Dry} is fixed costs associated with the use of dry applicator ($ per ton).

ϕ_{w}^{Dry} represents fixed cost of owning dry warehouse ($ per year).

Q_{s}^{Urea} is quantity of urea supplied by manufacturers or importers (tons).

Q_{f}^{Urea} is total demand for urea at farm level (tons).

CAP_{w}^{Dry} is storage capacity of dry warehouse (tons).

CAP_{a}^{Dry} is seasonal material capacity of dry applicator (tons).

Model 3

$$\text{Min } Z_3 = \sum_{s=1}^{2} \sum_{w=1}^{7} Q_{sw}^{DAP} \beta_{sw}^{DAP} + \sum_{s} \sum_{w=1}^{7} Q_{sw}^{Urea} \beta_{sw}^{Urea} + \sum_{w=1}^{7} \sum_{f=1}^{14} Q_{wf}^{DAP} \alpha_{wf}^{DAP} + \sum_{w=1}^{7} \sum_{f=1}^{14} Q_{wf}^{Urea} \alpha_{wf}^{Urea}$$
$$+ \sum_{a=1}^{7} \sum_{f=1}^{14} Q_{fa}^{Dry} \psi_{fa}^{Dry} + \sum_{a=1}^{7} \lambda_{a}^{Dry} X_{a}^{Dry} + \sum_{w=1}^{7} \phi_{w}^{Dry} X_{w}^{Dry}$$

Subject to:

$\sum_{w=1}^{7} Q_{sw}^{DAP} \le Q_{s}^{DAP} \ \forall s$ (DAP supply constraint)

$\sum_{w=1}^{7} Q_{sw}^{Urea} \le Q_{s}^{Urea} \ \forall s$ (urea supply constraint)

$\sum_{w=1}^{7} Q_{wf}^{DAP} \ge Q_{f}^{DAP} \ \forall f$ (satisfy DAP demand)

$\sum_{w=1}^{7} Q_{wf}^{Urea} \ge Q_{f}^{Urea} \ \forall f$ (satisfy urea demand)

$\sum_{f=1}^{14} Q_{wf}^{DAP} = \sum_{s=1} Q_{sw}^{DAP} \ \forall w$ (balanced DAP flow)

$\sum_{f=1}^{14} Q_{wf}^{Urea} = \sum_{s=2} Q_{sw}^{Urae} \ \forall w$ (balanced urea flow)

$\sum_{s=1} Q_{sw}^{DAP} + \sum_{s=2} Q_{sw}^{Urea} \le X_{w}^{Dry} \cdot CAP_{w}^{Dry} \ \forall w$ (storage constraint for dry fertilizers)

$\sum_{f=1}^{14} Q_{fa}^{Dry} \le X_{a}^{Dry} \cdot CAP_{a}^{Dry} \ \forall a$ (dry applicator capacity constraint)

$\sum_{w=1}^{7} Q_{wf}^{DAP} + \sum_{w=1}^{7} Q_{wf}^{Urea} = \sum_{a=1}^{7} Q_{fa}^{Dry} \ \forall f$ (application requirement for dry fertilizers)

$Q_{sw}^{DAP}, Q_{sw}^{Urea}, Q_{wf}^{DAP}, Q_{wf}^{Urea}, Q_{fa}^{Dry} \ge 0$ (non-negativity condition)

$X_{a}^{Dry} \in \{0, 1, 2, \ldots, n\}$ (integer solution for machinery selection)

$X_{w}^{Dry} \in \{0, 1\} \ \forall w = 1, 2, \ldots, 7$ (binary variables for warehouse construction)

In model 3, Z_3 is total cost for shipping, warehousing, and applying DAP and urea fertilizers. Other variables are defined in models 1 and 2.

Model 4

$$\begin{aligned}\text{Min } Z_4 = {} & \sum_{s=1}^{2}\sum_{w=1}^{7} Q_{sw}^{DAP}\beta_{sw}^{DAP} + \sum_{s}\sum_{w=1}^{7} Q_{sw}^{UAN}\beta_{sw}^{UAN} + \sum_{w=1}^{7}\sum_{f=1}^{14} Q_{wf}^{DAP}\alpha_{wf}^{DAP} + \sum_{w=1}^{7}\sum_{f=1}^{14} Q_{wf}^{UAN}\alpha_{wf}^{UAN} \\ & + \sum_{a=1}^{7}\sum_{f=1}^{14} Q_{fa}^{DAP}\psi_{fa}^{DAP} + \sum_{a=1}^{7}\sum_{f=1}^{14} Q_{fa}^{UAN}\psi_{fa}^{UAN} + \sum_{a=1}^{7}\lambda_{a}^{DAP}X_{a}^{DAP} + \sum_{a=1}^{7}\lambda_{a}^{UAN}X_{a}^{UAN} \\ & + \sum_{w=1}^{7}\phi_{w}^{DAP}X_{w}^{DAP} + \sum_{w=1}^{7}\phi_{w}^{UAN}X_{w}^{UAN}\end{aligned}$$

Subject to:

$$\sum_{w=1}^{7} Q_{sw}^{DAP} \le Q_{s}^{DAP} \quad \forall s \qquad \text{(DAP supply constraint)}$$

$$\sum_{w=1}^{7} Q_{sw}^{UAN} \le Q_{s}^{UAN} \quad \forall s \qquad \text{(UAN supply constraint)}$$

$$\sum_{w=1}^{7} Q_{wf}^{DAP} \ge Q_{f}^{DAP} \quad \forall f \qquad \text{(satisfy DAP demand)}$$

$$\sum_{w=1}^{7} Q_{wf}^{UAN} \ge Q_{f}^{UAN} \quad \forall f \qquad \text{(satisfy UAN demand)}$$

$$\sum_{f=1}^{14} Q_{wf}^{DAP} = \sum_{s=1} Q_{sw}^{DAP} \quad \forall w \qquad \text{(balanced DAP flow)}$$

$$\sum_{f=1}^{14} Q_{wf}^{UAN} = \sum_{s=3} Q_{sw}^{UAN} \quad \forall w \qquad \text{(balanced UAN flow)}$$

$$\sum_{s=1} Q_{sw}^{DAP} \le X_{w}^{DAP}\cdot CAP_{w}^{DAP} \quad \forall w \qquad \text{(storage constraint for DAP fertilizers)}$$

$$\sum_{s=3} Q_{sw}^{UAN} \le X_{w}^{UAN}\cdot CAP_{w}^{UAN} \quad \forall w \qquad \text{(storage constraint for UAN)}$$

$$\sum_{f=1}^{14} Q_{fa}^{DAP} \le X_{a}^{DAP}\cdot CAP_{a}^{DAP} \quad \forall a \qquad \text{(DAP applicator capacity constraint)}$$

$$\sum_{f=1}^{14} Q_{fa}^{UAN} \le X_{a}^{UAN}\cdot CAP_{a}^{UAN} \quad \forall a \qquad \text{(UAN applicator capacity constraint)}$$

$\sum_{w=1}^{7} Q_{wf}^{DAP} = \sum_{a=1}^{7} Q_{fa}^{DAP} \ \forall f$ (application requirement for DAP fertilizers)

$\sum_{w=1}^{7} Q_{wf}^{UAN} = \sum_{a=1}^{7} Q_{fa}^{UAN} \ \forall f$ (application requirement for UAN fertilizers).

$Q_{sw}^{DAP}, Q_{sw}^{UAN}, Q_{wf}^{DAP}, Q_{wf}^{UAN},$
$Q_{fa}^{DAP}, Q_{fa}^{UAN} \geq 0$ (non-negativity condition)

$X_{a}^{DAP},\ X_{a}^{UAN} \in \{0, 1, 2, \ldots, n\}$ (integer solution for machinery selection)

$X_{w}^{DAP},\ X_{w}^{UAN} \in \{0, 1\} \ \forall\, w = 1, 2, \ldots, 7$ (binary variables for warehouse construction)

In the above model, Z_4 is total cost for shipping, warehousing, and applying DAP and UAN. Other variables are defined in the first model.

APPENDIX 2

GAMS CODES

Capacitated Mixed Integer Model

```
$OFFSYMLIST OFFSYMXREF OFFUPPER
options limrow = 0, limcol = 0;

SETS
S1 Sources of DAP fertilizers /ENID, PCTOOSA/
S2 Source of UREA fertilizers /PCTOOSA/
S3 Source of LIQUID fertilizers /ENID/
S4 Sources of ANHYDROUS fertilizer /W-WARD, ENID/

*****************************************************************
**PTOOSA stands for Port of Catoosa                            **
**W-WARD stands for Woodward                                   **
**DAP stands for diammonium phosphate contains 18-46-0         **
**   (Nitrogen-Phosphate-Potash)**                             **
**UREA contains 46-0-0                                         **
**LIQUID stands for liquid ammonia (28-0-0)                    **
**ANHYDROUS stands for anhydrous ammonia (82-0-0)              **
*****************************************************************

W warehouses /CKing, King, Okar, Yuko, Omeg, Pied, Wato, Henn/
********************************************************************
**Names in W are in short form, they stand for Centralized Warehouse at  **
**  Kingfisher, Kingfisher, Okarche, Yukon,Omega, Piedmont, Watonga      **
**  and Hennessy respectively.                                           **
********************************************************************

A1 DAP-UREA applicators /DAPUR-CKing, DAPUR-King, DAPUR-Okar, DAPUR-Yuko
                        DAPUR-Omeg, DAPUR-Pied, DAPUR-Wato, DAPUR-Henn/

A2 UAN applicators /Liq-CKing, Liq-King,Liq-Okar, Liq-Yuko, Liq-Omeg,Liq-Pied,
                      Liq-Wato, Liq-Henn/

A3 ANHY applicator /Sanh-Cking, Sanh-King, Sanh-Okar, Sanh-Yuko, Sanh-Omeg
                    Sanh-Pied, Sanh-Wato, Sanh-Henn, Banh-Cking, Banh-King
                    Banh-Okar, Banh-Yuko, Banh-Omeg, Banh-Pied, Banh-Wato
                    Banh-Henn/

F field sizes and locations
 /Big-King, Big-Okar, Big-Yuko, Big-Omeg, Big-Pied,Big-Wato,Big-Henn,
  Small-King, Small-Okar,Small-Yuko, Small-Omeg,Small-Pied, Small-Wato,
  Small-Henn/
***********************************************************************
**Big-King means a big field at Kingfisher, Small-King means           **
**   a small field at Kingfisher.                                      **
**DAPUR-King means DAP & UREA applicator from Kingfisher               **
**Liq-King means a UAN ammonia applicator from Kingfisher              **
**Sanh-King means a small anhydrous applicator from Kingfisher         **
**Banh-King means a big anhydrous applicator from Kingfisher           **
***********************************************************************

ALIAS (A1,P1),(A2,P2), (A3, P3);

PARAMETER SUPDAP (S1) Total supply of DAP in metric tones
 /
 ENID      3000000
 PCTOOSA   4600000/

SUPUREA (S2) Total supply of UREA in metric tones
/
PCTOOSA    5500000 /

SUPLIQ (S3) Total supply of UAN in metric tones
/ENID       8400000/

SUPPANHY (S4) Total Supply of ANHYDROUS-AMMONIA in metric tones
/ENID       98000000
```

```
W-WARD      97600000/

******************************************************************************
**The supply is hypothetical, it is assumed not to be a constraining factor  **
******************************************************************************

************************************************************************
** ESTIMATION OF APPLICATORS' CAPACITIES AND CAPACITIES ADJUSTMENTS     **
** TO ACCOUNT FOR TRAVEL TIME (TO AND FROM FIELDS) AND BREAKDOWN TIME   **
************************************************************************

Scalars
GSPEED Road speed of the applicators in miles per hour /40/
*Source: Mid-Oklahoma Cooperatives
TRSPEED speed of trucks used to transport anhydrous applicators in miles per hour  /35/
*Source: Kenkel (Personal communication);

TABLE DISTDAPUR (A1,F) DAP-UREA applicator travel distance from warehouses to fields in
miles
             Big-King Big-Okar Big-Yuko Big-Omeg Big-Pied Big-Wato Big-Henn
DAPUR-CKing   5        9.70     32.67    27.30    30.20    40.50    29.70
DAPUR-King    5        9.70     32.67    27.30    30.20    40.50    29.70
DAPUR-Okar    9.70     5.00     28.40    30.60    26.00    43.80    33.00
DAPUR-Yuko    32.6     28.40    5        53.50    16.50    57.50    55.90
DAPUR-Omeg    27.3     30.60    53.50    5        43.50    18.20    38.80
DAPUR-Pied    30.20    26.00    16.50    43.50    5        56.70    45.90
DAPUR-Wato    40.50    43.80    57.50    18.20    56.70    5        52.00
DAPUR-Henn    29.70    33.00    55.90    38.80    45.90    52.00    5
+            Small-King Small-Okar Small-Yuko Small-Omeg Small-Pied Small-Wato Small-Henn
DAPUR-CKing   5          9.70       32.67      27.30      30.20      40.50      29.70
DAPUR-King    5          9.70       32.67      27.30      30.20      40.50      29.70
DAPUR-Okar    9.70       5.00       28.40      30.60      26.00      43.80      33.00
DAPUR-Yuko    32.6       28.40      5          53.50      16.50      57.50      55.90
DAPUR-Omeg    27.3       30.60      53.50      5          43.50      18.20      38.80
DAPUR-Pied    30.20      26.00      16.50      43.50      5          56.70      45.90
DAPUR-Wato    40.50      43.80      57.50      18.20      56.70      5          52.00
DAPUR-Henn    29.70      33.00      55.90      38.80      45.90      52.00      5;

TABLE DISTLIQ (A2,F) UAN applicator travel distance from warehouses to fields in miles
             Big-King Big-Okar Big-Yuko Big-Omeg Big-Pied Big-Wato Big-Henn
LIQ-CKing     5        9.70     32.67    27.30    30.20    40.50    29.70
LIQ-King      5        9.70     32.67    27.30    30.20    40.50    29.70
LIQ-Okar      9.70     5.00     28.40    30.60    26.00    43.80    33.00
LIQ-Yuko      32.6     28.40    5        53.50    16.50    57.50    55.90
LIQ-Omeg      27.3     30.60    53.50    5        43.50    18.20    38.80
LIQ-Pied      30.20    26.00    16.50    43.50    5        56.70    45.90
LIQ-Wato      40.50    43.80    57.50    18.20    56.70    5        52.00
LIQ-Henn      29.70    33.00    55.90    38.80    45.90    52.00    5
+            Small-King Small-Okar Small-Yuko Small-Omeg Small-Pied Small-Wato Small-Henn
LIQ-CKing     5          9.70       32.67      27.30      30.20      40.50      29.70
LIQ-King      5          9.70       32.67      27.30      30.20      40.50      29.70
LIQ-Okar      9.70       5.00       28.40      30.60      26.00      43.80      33.00
LIQ-Yuko      32.6       28.40      5          53.50      16.50      57.50      55.90
LIQ-Omeg      27.3       30.60      53.50      5          43.50      18.20      38.80
LIQ-Pied      30.20      26.00      16.50      43.50      5          56.70      45.90
LIQ-Wato      40.50      43.80      57.50      18.20      56.70      5          52.00
LIQ-Henn      29.70      33.00      55.90      38.80      45.90      52.00      5;
```

```
TABLE DISTANYD (A3,F) ANHYDROUS applicator travel distance from warehouses to fields in
miles
                 Big-King Big-Okar Big-Yuko Big-Omeg Big-Pied Big-Wato Big-Henn
Sanh-CKing        5        9.70      32.67    27.30     30.20  40.50     29.70
Sanh-King         5        9.70      32.67    27.30     30.20  40.50     29.70
Sanh-Okar        9.70      5.00      28.40    30.60     26.00  43.80     33.00
Sanh-Yuko        32.6      28.40     5        53.50     16.50  57.50     55.90
Sanh-Omeg        27.3      30.60     53.50    5         43.50  18.20     38.80
Sanh-Pied        30.20     26.00     16.50    43.50     5      56.70     45.90
Sanh-Wato        40.50     43.80     57.50    18.20     56.70  5         52.00
Sanh-Henn        29.70     33.00     55.90    38.80     45.90  52.00     5
Banh-CKing        5        9.70      32.67    27.30     30.20  40.50     29.70
Banh-King         5        9.70      32.67    27.30     30.20  40.50     29.70
Banh-Okar        9.70      5.00      28.40    30.60     26.00  43.80     33.00
Banh-Yuko        32.6      28.40     5        53.50     16.50  57.50     55.90
Banh-Omeg        27.3      30.60     53.50    5         43.50  18.20     38.80
Banh-Pied        30.20     26.00     16.50    43.50     5      56.70     45.90
Banh-Wato        40.50     43.80     57.50    18.20     56.70  5         52.00
Banh-Henn        29.70     33.00     55.90    38.80     45.90  52.00     5
+                Small-King Small-Okar Small-Yuko Small-Omeg Small-Pied Small-Wato Small-Henn
Sanh-CKing        5          9.70       32.67      27.30       30.20     40.50      29.70
Sanh-King         5          9.70       32.67      27.30       30.20     40.50      29.70
Sanh-Okar        9.70        5.00       28.40      30.60       26.00     43.80      33.00
Sanh-Yuko        32.6        28.40      5          53.50       16.50     57.50      55.90
Sanh-Omeg        27.3        30.60      53.50      5           43.50     18.20      38.80
Sanh-Pied        30.20       26.00      16.50      43.50       5         56.70      45.90
Sanh-Wato        40.50       43.80      57.50      18.20       56.70     5          52.00
Sanh-Henn        29.70       33.00      55.90      38.80       45.90     52.00      5
Banh-CKing        5          9.70       32.67      27.30       30.20     40.50      29.70
Banh-King         5          9.70       32.67      27.30       30.20     40.50      29.70
Banh-Okar        9.70        5.00       28.40      30.60       26.00     43.80      33.00
Banh-Yuko        32.6        28.40      5          53.50       16.50     57.50      55.90
Banh-Omeg        27.3        30.60      53.50      5           43.50     18.20      38.80
Banh-Pied        30.20       26.00      16.50      43.50       5         56.70      45.90
Banh-Wato        40.50       43.80      57.50      18.20       56.70     5          52.00
Banh-Henn        29.70       33.00      55.90      38.80       45.90     52.00      5;

**********************************************************************************
*The assumption is that fields closer to any of the warehouses are about 5 miles away.***
*Actual distances were calculated using a distance finder (http:/www.mapblast.com)    ***
**********************************************************************************
Parameters
TIMEDAPUR (A1,F) DAP-UREA applicator round trip travel time to and from fields in hours
TIMELIQ (A2,F) UAN applicator round trip travel time to and from fields in hours
TIMEANHY (A3,F) ANHYDROUS applicator round trip travel time to and from fields in hours;
TIMEDAPUR (A1,F)=2*(DISTDAPUR(A1,F)/GSPEED);
TIMELIQ (A2,F)=2*(DISTLIQ(A2,F)/GSPEED);
TIMEANHY (A3,F)=2*(DISTANYD (A3,F)/TRSPEED);

Table FSDAPUR (A1,F)  Field Speed of DAP-UREA applicator in miles per hour
               Big-King Big-Okar Big-Yuko Big-Omeg Big-Pied Big-Wato Big-Henn
DAPUR-CKing    16.5      16.5      16.5    16.5      16.5       16.5      16.5
DAPUR-King     16.5      16.5      16.5    16.5      16.5       16.5      16.5
DAPUR-Okar     16.5      16.5      16.5    16.5      16.5       16.5      16.5
DAPUR-Yuko     16.5      16.5      16.5    16.5      16.5       16.5      16.5
DAPUR-Omeg     16.5      16.5      16.5    16.5      16.5       16.5      16.5
DAPUR-Pied     16.5      16.5      16.5    16.5      16.5       16.5      16.5
DAPUR-Wato     16.5      16.5      16.5    16.5      16.5       16.5      16.5
DAPUR-Henn     16.5      16.5      16.5    16.5      16.5       16.5      16.5
+              Small-King Small-Okar Small-Yuko Small-Omeg Small-Pied Small-Wato Small-Henn
DAPUR-CKing    16.5        16.5        16.5       16.5        16.5          16.5      16.5
DAPUR-King     16.5        16.5        16.5       16.5        16.5          16.5      16.5
DAPUR-Okar     16.5        16.5        16.5       16.5        16.5          16.5      16.5
DAPUR-Yuko     16.5        16.5        16.5       16.5        16.5          16.5      16.5
DAPUR-Omeg     16.5        16.5        16.5       16.5        16.5          16.5      16.5
DAPUR-Pied     16.5        16.5        16.5       16.5        16.5          16.5      16.5
DAPUR-Wato     16.5        16.5        16.5       16.5        16.5          16.5      16.5
DAPUR-Henn     16.5        16.5        16.5       16.5        16.5          16.5      16.5;
*Source: Mid-Oklahoma Cooperatives
```

```
Table FSLIQ (A2,F) Field Speed of UAN applicators in miles per hour
                 Big-King Big-Okar Big-Yuko Big-Omeg Big-Pied Big-Wato Big-Henn
Liq-CKing    19          19          19        19         19          19          19
Liq-King     19          19          19        19         19          19          19
Liq-Okar     19          19          19        19         19          19          19
Liq-Yuko     19          19          19        19         19          19          19
Liq-Omeg     19          19          19        19         19          19          19
Liq-Pied     19          19          19        19         19          19          19
Liq-Wato     19          19          19        19         19          19          19
Liq-Henn     19          19          19        19         19          19          19
+              Small-King Small-Okar Small-Yuko Small-Omeg Small-Pied Small-Wato Small-Henn
Liq-CKing    19          19           19         19           19          19         19
Liq-King     19          19           19         19           19          19         19
Liq-Okar     19          19           19         19           19          19         19
Liq-Yuko     19          19           19         19           19          19         19
Liq-Omeg     19          19           19         19           19          19         19
Liq-Pied     19          19           19         19           19          19         19
Liq-Wato     19          19           19         19           19          19         19
Liq-Henn     19          19           19         19           19          19         19 ;
*Source: Mid-Oklahoma Cooperatives
```

```
Table FSNAHYD (A3,F) Field Speed of ANHYDROUS applicators in miles per hour
                 Big-King Big-Okar Big-Yuko Big-Omeg Big-Pied Big-Wato Big-Henn
Sanh-CKing    5          5          5          5          5          5          5
Sanh-King     5          5          5          5          5          5          5
Sanh-Okar     5          5          5          5          5          5          5
Sanh-Yuko     5          5          5          5          5          5          5
Sanh-Omeg     5          5          5          5          5          5          5
Sanh-Pied     5          5          5          5          5          5          5
Sanh-Wato     5          5          5          5          5          5          5
Sanh-Henn     5          5          5          5          5          5          5
Banh-CKing    5          5          5          5          5          5          5
Banh-King     5          5          5          5          5          5          5
Banh-Okar     5          5          5          5          5          5          5
Banh-Yuko     5          5          5          5          5          5          5
Banh-Omeg     5          5          5          5          5          5          5
Banh-Pied     5          5          5          5          5          5          5
Banh-Wato     5          5          5          5          5          5          5
Banh-Henn     5          5          5          5          5          5          5

+                Small-King Small-Okar Small-Yuko Small-Omeg Small-Pied Small-Wato Small-Henn
Sanh-CKing    5          5           5          5           5           5           5
Sanh-King     5          5           5          5           5           5           5
Sanh-Okar     5          5           5          5           5           5           5
Sanh-Yuko     5          5           5          5           5           5           5
Sanh-Omeg     5          5           5          5           5           5           5
Sanh-Pied     5          5           5          5           5           5           5
Sanh-Wato     5          5           5          5           5           5           5
Sanh-Henn     5          5           5          5           5           5           5
Banh-CKing    5          5           5          5           5           5           5
Banh-King     5          5           5          5           5           5           5
Banh-Okar     5          5           5          5           5           5           5
Banh-Yuko     5          5           5          5           5           5           5
Banh-Omeg     5          5           5          5           5           5           5
Banh-Pied     5          5           5          5           5           5           5
Banh-Wato     5          5           5          5           5           5           5
Banh-Henn     5          5           5          5           5           5           5;
*Souce: Siemens and Kirwan (1997)
```

```
Table SANHWIDT (A3,F) Working width of ANHYDROUS applicators in ft
            Big-King Big-Okar Big-Yuko Big-Omeg Big-Pied Big-Wato Big-Henn
Sanh-CKing   20        20       20       20       20       20       20
Sanh-King    20        20       20       20       20       20       20
Sanh-Okar    20        20       20       20       20       20       20
Sanh-Yuko    20        20       20       20       20       20       20
Sanh-Omeg    20        20       20       20       20       20       20
Sanh-Pied    20        20       20       20       20       20       20
Sanh-Wato    20        20       20       20       20       20       20
Sanh-Henn    20        20       20       20       20       20       20
Banh-CKing   30        30       30       30       30       30       30
Banh-King    30        30       30       30       30       30       30
Banh-Okar    30        30       30       30       30       30       30
Banh-Yuko    30        30       30       30       30       30       30
Banh-Omeg    30        30       30       30       30       30       30
Banh-Pied    30        30       30       30       30       30       30
Banh-Wato    30        30       30       30       30       30       30
Banh-Henn    30        30       30       30       30       30       30

+          Small-King Small-Okar Small-Yuko Small-Omeg Small-Pied Small-Wato Small-Henn
Sanh-CKing   20         20          20         20         20         20         20
Sanh-King    20         20          20         20         20         20         20
Sanh-Okar    20         20          20         20         20         20         20
Sanh-Yuko    20         20          20         20         20         20         20
Sanh-Omeg    20         20          20         20         20         20         20
Sanh-Pied    20         20          20         20         20         20         20
Sanh-Wato    20         20          20         20         20         20         20
Sanh-Henn    20         20          20         20         20         20         20
Banh-CKing   30         30          30         30         30         30         30
Banh-King    30         30          30         30         30         30         30
Banh-Okar    30         30          30         30         30         30         30
Banh-Yuko    30         30          30         30         30         30         30
Banh-Omeg    30         30          30         30         30         30         30
Banh-Pied    30         30          30         30         30         30         30
Banh-Wato    30         30          30         30         30         30         30
Banh-Henn    30         30          30         30         30         30         30 ;
*Souce: Harryman, Siemens and Kirwan (1997)

Scalars
AEF Dry and UAN applicator efficiency factor in percentage /0.7/
AEF2 anhydrous applicator efficiency factor in percentage  /0.8/
DRYWIDTH Dry applicator working width in ft /60/
LIQWIDTH UAN applicator working width in ft /75/
RATEDAP DAP application rate in metric tons per acre /0.027173913/
*DAP is the only source of potash: The application rate is constant for all systems

*******************************************************************************************
**The application rates are calculated based on USDA fertilizer use statistics.         **
**Oklahoma wheat needs 95 pounds of N/acre and 25 pounds of P205/acre.                  **
**The application rates are calculated based on percentage contributions                **
**  to total nitrogen and potash that was demanded in year 2002.                        **
**DAP and UREA are normally mixed together when applied.                                **
*******************************************************************************************
Scalar
****************************************************
*THESE ARE APPLICATION RATES FOR HIGH YIELD GOAL***
****************************************************
RATEANH3 ANHYDROUS application rate in metric tons per acre for application system1
/0.045855577/
RATLIQ2 UAN application rate in metric tons per acre for application system4
/0.152157143/
RATLIQ3 UAN application rate in metric tons per acre for application system1
/0.017865809/
RATEURE1 UREA application rate in metric tons per acre for application system3
/0.092627599/
RATLIQ4 UAN application rate in metric tons per acre for application system2
/0.017865809/
RATEURE4 UREA application rate in metric tons per acre for application system2
/0.081742551/
RATDAUR4 DAP-UREA application rate in tons per acre for application system2
RATDAUR1 DAP-UREA application rate in tons per acre for application system3;
```

```
RATDAUR1=RATEDAP+RATEURE1;
RATDAUR4=RATEDAP+RATEURE4;
*********************************************************************************
**The assumption is that the N and P205 demand could be met through applying any      **
**    of the following combinations: DAP+ANHYDROUS+LIQUID, DAP+UAN+UREA, DAP+UREA     **
**    and DAP+UAN                                                                     **
**The four combinations are called system1, system2, system3 and system4,             **
**    respectively                                                                    **
*********************************************************************************

*********************************************************************************
** The application rates specified below were used to account for possible deviations **
**  in the N-application rate and are approximations to the 69 pounds of N suggested  **
**  by Hossain, Epplin, Horn, and Krenzer, Jr.                                        **
*********************************************************************************
*RATEANH3 ANHYDROUS application rate in metric tons per acre for application system1
/0.032401566/
*RATLIQ2 UAN application rate in metric tons per acre for application system4
/0.107514286/
*RATLIQ3 UAN application rate in metric tons per acre for application system1
/0.012623987/
*RATEURE1 UREA application rate in metric tons per acre for application system3
/0.065443478/
*RATLIQ4 UAN application rate in metric tons per acre for application system2
/0.012623987/
*RATEURE4 UREA application rate in metric tons per acre for application system2
/0.057759313/
*RATDAUR4 DAP-UREA application rate in tons per acre for application system2
*RATDAUR1 DAP-UREA application rate in tons per acre for application system3;
*RATDAUR1=RATEDAP+RATEURE1;
*RATDAUR4=RATEDAP+RATEURE4;

Parameters
MIXFCAP (A1,F) DAP-UREA applicator field capacities in acres per hour
LIQFCAP (A2,F) UAN applicator field capacities in acres per hour
ANHYFCAP (A3,F) ANHYDROUS applicator field capacity in acres per hour
MIXMCAP1 (A1,F) System3_material capacity for DAP-UREA applicator in tons per hour
DAPMCAP23 (A1,F) Systems1&4_material capacity for DAP applicator in tons per hour
MIXMCAP4 (A1,F) System2_material capacity for DAP-UREA applicator in tons per hour
LIQMCAP2 (A2,F) System4_UAN applicator material capacity in tons per hour
LIQMCAP3 (A2,F) System1_UAN applicator material capacity in tons per hour
LIQMCAP4 (A2,F) System2_UAN applicator material capacity in tons per hour
ANHYMCAP3 (A3,F) System1_ANHYDROUS applicator material capacity in tons per hour;
MIXFCAP (A1,F)=(FSDAPUR(A1,F)*DRYWIDTH *AEF)/8.25;
LIQFCAP (A2,F)=(FSLIQ(A2,F)*LIQWIDTH *AEF)/8.25;
ANHYFCAP (A3,F)=(FSNAHYD (A3,F)*SANHWIDT (A3,F)*AEF2)/8.25;
MIXMCAP1 (A1,F)=(FSDAPUR(A1,F)*DRYWIDTH*RATDAUR1 *AEF)/8.25;
DAPMCAP23  (A1,F)=(FSDAPUR(A1,F)*DRYWIDTH*RATEDAP *AEF)/8.25;
MIXMCAP4 (A1,F)=(FSDAPUR(A1,F)*DRYWIDTH*RATDAUR4 *AEF)/8.25;
LIQMCAP2 (A2,F)=(FSLIQ(A2,F)*LIQWIDTH*RATLIQ2 *AEF)/8.25;
LIQMCAP3 (A2,F)=(FSLIQ(A2,F)*LIQWIDTH*RATLIQ3 *AEF)/8.25;
LIQMCAP4 (A2,F)=(FSLIQ(A2,F)*LIQWIDTH*RATLIQ4 *AEF)/8.25;
ANHYMCAP3 (A3,F)=(FSNAHYD (A3,F)*SANHWIDT(A3,F)*RATEANH3*AEF2)/8.25;
*Source: American Society of Agricultural Engineers (ASAE)
*The coefficient 8.25 is a ratio calculated as: 43000 square ft per acre/5280 ft per mile


Scalar
AWHPY1 Dry applicators' average working hours per year /450/
AWHPY2 Liquid applicator average working hours per year /210/
*Source: Kenkel (Personal Communication)
*ANHYWHPY Anhydrous applicator working hours per year /168/
ANHYWHPY Anhydrous applicator working hours per year /210/
*Source: Harryman, Siemens and Kirwan (1997)
AWHPD applicators' average working hours per day (DRY AND UAN) /10/
*Source: Mid-Oklahoma Cooperatives
ANYHPD ANHYDROUS applicator effective working hours per day /8/
*Source: Mid-Oklahoma Cooperatives
ABTDD DRY applicator breakdown time
ABTDL UAN applicator breakdown time
ANHYBT Anhydrous applicator breakdown time
```

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BDPSDD DRY applicator breakdown probability per season
BDPSDL UAN applicator breakdown probability per season
BDPFDD DRY applicator breakdown probability per field
BDPFDL UAN applicator breakdown probability per field
ANYHDS ANHDROUS applicator breakdown probability per season
ANYDHSF ANHYDROUS applicator breakdown probability per field;
ABTDD= 0.0003234*(AWHPY1)**1.4173;
ABTDL= 0.0003234*(AWHPY2)**1.4173;
*Source: ASAE
ANHYBT=0.0003234*(ANHYWHPY)**1.4173;
*Source: ASAE
BDPSDD=(ABTDD/AWHPY1);
BDPSDL=(ABTDL/AWHPY2);
ANYHDS=(ANHYBT/ANHYWHPY);
BDPFDD=BDPSDD**14;
BDPFDL=BDPSDL**14;
ANYDHSF=ANYHDS**14;
Parameters
DAPURCAP1 (A1,F)  Adjusted daily material capacity of DAP-UREA applicator_system3
DAPCAP23 (A1,F)   Adjusted daily material capacity of DAP applicator_system1&4
DAPURCAP4 (A1,F)  Adjusted daily material capacity of DAP-UREA applicator_system2
LIQCAP2 (A2,F)    Adjusted daily material capacity of UAN applicator_system4
LIQCAP3 (A2,F)    Adjusted daily material capacity of UAN applicator_system1
LIQCAP4 (A2,F)    Adjusted daily material capacity of UAN applicator_system2
ANHYDCAP3 (A3,F) Adjusted daily material capacity of ANHYDROUS  applicator_system1;
DAPURCAP1(A1,F)=(AWHPD-TIMEDAPUR(A1,F)-(AWHPD-TIMEDAPUR(A1,F))*BDPFDD)*MIXMCAP1(A1,F);
DAPCAP23 (A1,F)=(AWHPD-TIMEDAPUR(A1,F)-(AWHPD-TIMEDAPUR(A1,F))*BDPFDD)*DAPMCAP23(A1,F);
DAPURCAP4(A1,F)=(AWHPD-TIMEDAPUR(A1,F)-(AWHPD-TIMEDAPUR(A1,F))*BDPFDD)*MIXMCAP4(A1,F);
LIQCAP2(A2,F)=(AWHPD-TIMELIQ(A2,F)-(AWHPD-TIMELIQ(A2,F))*BDPFDL)*LIQMCAP2(A2,F);
LIQCAP3(A2,F)=(AWHPD-TIMELIQ(A2,F)-(AWHPD-TIMELIQ(A2,F))*BDPFDL)*LIQMCAP3(A2,F);
LIQCAP4(A2,F)=(AWHPD-TIMELIQ(A2,F)-(AWHPD-TIMELIQ(A2,F))*BDPFDL)*LIQMCAP4(A2,F);
ANHYDCAP3 (A3,F)=(ANYHPD-TIMEANHY (A3,F)-(ANYHPD-TIMEANHY
(A3,F))*ANYDHSF)*ANHYMCAP3(A3,F);


Scalar
DAYSFALL   applicators working days in FALL season   /45/
DAYSSPR    applicators working days in SPRING season  /21/
*Source: Mid-Oklahoma Cooperatives.
*****************************************************************
** Fall application (dry and anhydrous) has to done within 45 days      **
** Spring application (liquid) has to be done within 21 days           **
*****************************************************************
Parameter
DAURTCAP1(A1) seasonal material capacity of the DAP-UREA applicators_system3
DATCAP23(A1) seasonal material capacity of the DAP applicators_system1&4
DAURTCAP4(A1) seasonal material capacity of the DAP-UREA applicators_system2
LITMCAP2(A2) seasonal material capacity of the  UAN applicators_ system4
LITMCAP3(A2) seasonal material capacity of the UAN applicators_ system1
LITMCAP4(A2) seasonal material capacity of the UAN applicators_ system2
ANTMCAP3(A3) seasonal material capacity of ANYDROUS applicator_system1;
DAURTCAP1(P1)=SUM(F, DAPURCAP1(P1,F))*(DAYSFALL/14);
DATCAP23(P1)= SUM(F, DAPCAP23(P1,F))*(DAYSFALL/14);
DAURTCAP4(P1)=SUM(F, DAPURCAP4(P1,F))*(DAYSFALL/14);
LITMCAP2(P2)=SUM(F,LIQCAP2(P2,F))*(DAYSSPR/14);
LITMCAP3(P2)=SUM(F,LIQCAP3(P2,F))*(DAYSSPR/14);
LITMCAP4(P2)=SUM(F,LIQCAP4(P2,F))*(DAYSSPR/14);
ANTMCAP3(P3)=SUM(F,ANHYDCAP3 (P3,F))*(DAYSFALL/14);
```

```
*************************************************************
**ESTIMATION OF APPLICATOR COSTS (VARIABLE AND FIXED COSTS)**
*************************************************************

*****************************************
**1) FUEL COST AND OIL COST ESTIMATION*
*****************************************
Scalars
ATFP After tax average diesel price for year 2002 in U.S dollars per gallon /1.41/
*Source: Lundberg Survey, Inc.
AHP Horse power of applicators /325/
*Source: Mid-Oklahoma Coops
SFCRA fuel consumption rates for dry applicators in gallons per hour;
SFCRA=(0.73*0.06*AHP);
*Source: ASAE

Parameter
MIFCOST1(P1,F) DAP-UREA applicators fuel cost per ton in U.S dollars_system3
DAFCOST23(P1,F) DAP applicators fuel cost per ton in U.S dollars_system1&4
MIFCOST4(P1,F) DAP-UREA applicators fuel cost per ton in U.S dollars_system2
LIFCOST2(P2,F) UAN applicators fuel cost per ton in U.S dollars_system4
LIFCOST3(P2,F) UAN applicators fuel cost per ton in U.S dollars_system1
LIFCOST4(P2,F) UAN applicators fuel cost per ton in U.S dollars_system2
MIOCOST1(P1,F) DAP-UREA applicators oil cost per ton_system3
DAOCOST23(P1,F) DAP applicators oil cost per ton_system1&4
MIOCOST4(P1,F) DAP-UREA applicators oil cost per ton_system2
LIOCOST2(P2,F) UAN applicators oil cost per ton_system4
LIOCOST3(P2,F) UAN applicators oil cost per ton_system1
LIOCOST4(P2,F) UAN applicators oil cost per ton_system2;
MIFCOST1(P1,F)=((0.06*ATFP*AHP)/MIXFCAP(P1,F))/RATDAUR1;
DAFCOST23(P1,F)=((0.06*ATFP*AHP)/MIXFCAP(P1,F))/RATEDAP;
MIFCOST4(P1,F)=((0.06*ATFP*AHP)/MIXFCAP(P1,F))/RATDAUR4;
LIFCOST2  (P2,F)=((0.06*ATFP*AHP)/LIQFCAP  (P2,F))/RATLIQ2;
LIFCOST3  (P2,F)=((0.06*ATFP*AHP)/LIQFCAP  (P2,F))/RATLIQ3;
LIFCOST4  (P2,F)=((0.06*ATFP*AHP)/LIQFCAP  (P2,F))/RATLIQ4;
MIOCOST1  (P1,F)=(MIFCOST1(P1,F)*0.15);
DAOCOST23(P1,F)=(DAFCOST23(P1,F)*0.15);
MIOCOST4  (P1,F)=(MIFCOST4(P1,F)*0.15);
LIOCOST2  (P2,F)=(LIFCOST2(P2,F)*0.15);
LIOCOST3  (P2,F)=(LIFCOST3(P2,F)*0.15);
LIOCOST4  (P2,F)=(LIFCOST4(P2,F)*0.15);

*********************************************************************
**Oil cost is 15% of fuel cost (Dahl, Cobia and Dooley, and Cross)**
*********************************************************************

************************************************
**2) ESTIMATION OF REPAIR AND MAINTANANCE COST**
************************************************

Scalars
RF1 Repair factor 1 for dry and UAN applicators /0.04/
RF2 Repair factor 2 for dry and UAN applicators /2.1/
*Source: ASAE (I assume that applicators costs are similar to costs of
*        Self-propelled combines)
H Total hours of accumulated use at the beginning of year 2002 /0/
PM Price of machine in dollars /200000/;
*Source: Mid-Oklahoma coops

Parameter
MIRCOST1(P1,F) DAP-UREA  applicator repair cost in dollars per ton_system3
DARCOST23(P1,F) DAP applicator repair cost in dollars per ton_systems1&4
MIRCOST4(P1,F) DAP-UREA  applicator repair cost in dollars per ton_system2
LIRCOST2(P2,F) UAN applicator repair cost in dollars per ton_system4
LIRCOST3(P2,F) UAN applicator repair cost in dollars per ton_system1
LIRCOST4(P2,F) UAN applicator repair cost in dollars per ton_system2;
MIRCOST1(P1,F)=((PM*RF1*((AWHPY1+H)/1000)**RF2-PM*RF1
               *(H/1000)**RF2)/(AWHPY1*MIXFCAP (P1,F)))/RATDAUR1;
DARCOST23(P1,F)= ((PM*RF1*((AWHPY1+H)/1000)**RF2-PM*RF1
               *(H/1000)**RF2)/(AWHPY1*MIXFCAP (P1,F)))/RATEDAP;
MIRCOST4(P1,F)=((PM*RF1*((AWHPY1+H)/1000)**RF2-PM*RF1
```

```
                 *(H/1000)**RF2)/(AWHPY1*MIXFCAP (P1,F)))/RATDAUR4;
 LIRCOST2(P2,F)=((PM*RF1*((AWHPY2+H)/1000)**RF2-PM*RF1
                 *(H/1000)**RF2)/(AWHPY2*LIQFCAP (P2,F)))/RATLIQ2;
 LIRCOST3(P2,F)=((PM*RF1*((AWHPY2+H)/1000)**RF2-PM*RF1
                 *(H/1000)**RF2)/(AWHPY2*LIQFCAP (P2,F)))/RATLIQ3;
 LIRCOST4(P2,F)=((PM*RF1*((AWHPY2+H)/1000)**RF2-PM*RF1
                 *(H/1000)**RF2)/(AWHPY2*LIQFCAP (P2,F)))/RATLIQ4;

 DISPLAY MIRCOST1, DARCOST23, MIRCOST4, LIRCOST2, LIRCOST3, LIRCOST4;

 *********************************
 ** 3) ESTIMATION OF LABOR COST**
 *********************************
 Scalars
 PL Oklahoma hourly wage for farm workers /7.77/;
 **********************************************
 *Source: Oklahoma City MSA Wage data (2002)**
 **********************************************
 Parameter
 MILCOST1 (P1,F) DAP-UREA applicators labor cost in dollars per ton_system3
 DALCOST23 (P1,F) DAP applicators labor cost in dollars per ton_systems1&4
 MILCOST4 (P1,F) DAP-UREA applicators labor cost in dollars per ton_system2
 LILCOST2 (P2,F) UAN applicators labor cost in dollars per ton_system4
 LILCOST3 (P2,F) UAN applicators labor cost in dollars per ton_system1
 LILCOST4 (P2,F) UAN applicators labor cost in dollars per ton_system2;
 MILCOST1(P1,F)=(PL*1.25*(1/MIXFCAP (P1,F)))/RATDAUR1;
 DALCOST23 (P1,F)=(PL*1.25*(1/MIXFCAP (P1,F)))/RATEDAP;
 MILCOST4(P1,F)=(PL*1.25*(1/MIXFCAP (P1,F)))/RATDAUR4;
 LILCOST2(P2,F)=(PL*1.25*(1/LIQFCAP (P2,F)))/RATLIQ2;
 LILCOST3(P2,F)=(PL*1.25*(1/LIQFCAP (P2,F)))/RATLIQ3;
 LILCOST4(P2,F)=(PL*1.25*(1/LIQFCAP (P2,F)))/RATLIQ4;

 DISPLAY MILCOST1, DALCOST23, MILCOST4, LILCOST2, LILCOST3, LILCOST4;

 *****************************************
 ** 4) ESTIMATION OF DEPRECIATION COST***
 *****************************************
 Scalars
 DF1 Depreciation factor 1 /1.1318/
 DF2 Depreciation factor 2 /0.1645/
 DF3 Depreciation factor 3 /0.0079/
 AHYDEPCOST ANHYDROUS applicator depreciation cost per acre /1.94/;

 PARAMETER
 AHCOSTPT3(A3,F) ANHYDROUS applicator depreciation cost per acre_system1;
 *AHCOSTPT3 (A3,F)= AHYDEPCOST/RATEANH3;
 AHCOSTPT3 (A3,F)= (AHYDEPCOST/RATEANH3)*RATEANH3;

 *******************************************************************
 ** Sources:                                                      **
 **    Depreciation factors and formula: ASAE                     **
 **    AHYDEPCOST: Razarus and Selly (2002)                       **
 *******************************************************************

 Parameter
 MIDCOST1(P1,F) DAP-UREA applicator depreciation cost in dollars per acre_system3
 DADCOST23(P1,F) DAP applicator depreciation cost in dollars per acre_system1&4
 MIDCOST4(P1,F) DAP-UREA applicator depreciation cost in dollars per acre_system2
 LIDCOST2(P2,F) UAN applicator depreciation cost in dollars per acre_system4
 LIDCOST3(P2,F) UAN applicator depreciation cost in dollars per acre_system1
 LIDCOST4(P2,F) UAN applicator depreciation cost in dollars per acre_system2
 RV1 Remaining value for dry applicators at the end of year 2002
 RV2 Remaining value for liquid applicators at the end of year 2002;
 RV1=PM*(DF1-DF2*(1**0.5)-DF3*(AWHPY1**0.5))**2;
 RV2=PM*(DF1-DF2*(1**0.5)-DF3*(AWHPY2**0.5))**2;
 *Source: ASAE
 MIDCOST1(P1,F)=((PM-RV1)/(AWHPY1*MIXFCAP (P1,F)));
 DADCOST23(P1,F)= ((PM-RV1)/(AWHPY1*MIXFCAP (P1,F)));
 MIDCOST4(P1,F)=((PM-RV1)/(AWHPY1*MIXFCAP (P1,F)));
 LIDCOST2(P2,F)=((PM-RV2)/(AWHPY2*LIQFCAP (P2,F)));
 LIDCOST3(P2,F)=((PM-RV2)/(AWHPY2*LIQFCAP (P2,F)));
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LIDCOST4(P2,F)=((PM-RV2)/(AWHPY2*LIQFCAP (P2,F)));

*Source: Cross, 1998.

DISPLAY MIDCOST1, DADCOST23, MIDCOST4, LIDCOST2, LIDCOST3, LIDCOST4;
**********************************
**5) ESTIMATION OF INTEREST COST**
**********************************
Scalar
INT Interest rate /0.05/
***********************************************************************
**Source: Langemeir and Taylor (1998)                                **
***********************************************************************

Table ANHPRICE (A3,F) List prices of ANHYDROUS applicators in dollars
           Big-King Big-Okar Big-Yuko Big-Omeg Big-Pied Big-Wato Big-Henn
Sanh-CKing   9296     9296      9296    9296    9296     9296      9296
Sanh-King    9296     9296      9296    9296    9296     9296      9296
Sanh-Okar    9296     9296      9296    9296    9296     9296      9296
Sanh-Yuko    9296     9296      9296    9296    9296     9296      9296
Sanh-Omeg    9296     9296      9296    9296    9296     9296      9296
Sanh-Pied    9296     9296      9296    9296    9296     9296      92960
Sanh-Wato    9296     9296      9296    9296    9296     9296      9296
Sanh-Henn    9296     9296      9296    9296    9296     9296      9296
Banh-CKing   16800    16800     16800   16800   16800    16800     16800
Banh-King    16800    16800     16800   16800   16800    16800     16800
Banh-Okar    16800    16800     16800   16800   16800    16800     16800
Banh-Yuko    16800    16800     16800   16800   16800    16800     16800
Banh-Omeg    16800    16800     16800   16800   16800    16800     16800
Banh-Pied    16800    16800     16800   16800   16800    16800     16800
Banh-Wato    16800    16800     16800   16800   16800    16800     16800
Banh-Henn    16800    16800     16800   16800   16800    16800     16800
+          Small-King Small-Okar Small-Yuko Small-Omeg Small-Pied Small-Wato Small-Henn
Sanh-CKing   9296     9296        9296        9296        9296       9296         9296
Sanh-King    9296     9296        9296        9296        9296       9296         9296
Sanh-Okar    9296     9296        9296        9296        9296       9296         9296
Sanh-Yuko    9296     9296        9296        9296        9296       9296         9296
Sanh-Omeg    9296     9296        9296        9296        9296       9296         9296
Sanh-Pied    9296     9296        9296        9296        9296       9296         9296
Sanh-Wato    9296     9296        9296        9296        9296       9296         9296
Sanh-Henn    9296     9296        9296        9296        9296       9296         9296
Banh-CKing   16800    16800       16800       16800       16800      16800        16800
Banh-King    16800    16800       16800       16800       16800      16800        16800
Banh-Okar    16800    16800       16800       16800       16800      16800        16800
Banh-Yuko    16800    16800       16800       16800       16800      16800        16800
Banh-Omeg    16800    16800       16800       16800       16800      16800        16800
Banh-Pied    16800    16800       16800       16800       16800      16800        16800
Banh-Wato    16800    16800       16800       16800       16800      16800        16800
Banh-Henn    16800    16800       16800       16800       16800      16800        16800;
*Source: Siemens and Kirwan (1997)
```

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Parameter
MIICOST1 (P1,F) DAPUR applicators interest cost per acre_system3
DAICOST23 (P1,F) DAP applicators interest cost per acre_system1&4
MIICOST4 (P1,F) DAPUR applicators interest cost per acre_system2
LIICOST2 (P2,F) UAN applicators interest cost per acre_system4
LIICOST3 (P2,F) UAN applicators interest cost per acre_system1
LIICOST4 (P2,F) UAN applicators interest cost per acre_system2
REMVAHYD (P3,F) Remaining value of AHYDROUS applicators in the first year of use
AHISICOS3 (P3,F) ANHDROUS applicator interest cost per acre;
MIICOST1 (P1,F)=INT*RV1/(AWHPY1*MIXFCAP (P1,F));
DAICOST23 (P1,F)=INT*RV1/(AWHPY1*MIXFCAP (P1,F));
MIICOST4 (P1,F)=INT*RV1/(AWHPY1*MIXFCAP (P1,F));
LIICOST2 (P2,F)=INT*RV2/(AWHPY2*LIQFCAP (P2,F));
LIICOST3 (P2,F)=INT*RV2/(AWHPY2*LIQFCAP (P2,F));
LIICOST4 (P2,F)=INT*RV2/(AWHPY2*LIQFCAP (P2,F));
REMVAHYD (P3,F)= 60*0.885*ANHPRICE (P3,F)/100;
AHISICOS3 (P3,F)=(INT*REMVAHYD (P3,F)/(ANHYWHPY*ANHYFCAP (P3,F)));

***********************************
* 6) ESTIMATION OF INSURANCE COST**
***********************************
Scalar
INRATE Insurance rate as percentage of list price /0.25/
*******************
** Source: ASAE  **
*******************

Parameter
MIINCOST1(P1,F) DAP-UREA applicator insurance cost per acre in dollars_system3
DAINCOST23(P1,F) DAP applicator insurance cost per acre in dollars_system1&4
MIINCOST4(P1,F) DAP-UREA applicator insurance cost per acre in dollars_system2
LIINCOST2(P2,F) LIQUID applicator insurance cost per acre in dollars_system4
LIINCOST3(P2,F) LIQUID applicator insurance cost per acre in dollars_system1
LIINCOST4(P2,F) LIQUID applicator insurance cost per acre in dollars_system2
AHSINCOS3(P3,F) ANHYDROUS applicator insurance cost per acre in dollars_system1;
MIINCOST1(P1,F)=(PM*(INRATE/100)/(MIXFCAP (P1,F)*AWHPY1));
DAINCOST23(P1,F)=(PM*(INRATE/100)/(MIXFCAP (P1,F)*AWHPY1));
MIINCOST4(P1,F)=(PM*(INRATE/100)/(MIXFCAP (P1,F)*AWHPY1));
LIINCOST2(P2,F)=(PM*(INRATE/100)/(LIQFCAP (P2,F)*AWHPY2));
LIINCOST3(P2,F)=(PM*(INRATE/100)/(LIQFCAP (P2,F)*AWHPY2));
LIINCOST4(P2,F)=(PM*(INRATE/100)/(LIQFCAP (P2,F)*AWHPY2));
AHSINCOS3(P3,F)=(ANHPRICE (P3,F)*(INRATE/100)/(ANHYFCAP (P3,F)
                *ANHYWHPY));

Parameters
TFCMIX1 (P1,F) DAP-UREA applicator total fixed cost per acre in dollars_system3
TFCDAP23 (P1,F) DAP-UREA applicator total fixed cost per acre in dollars_system1&4
TFCMIX4 (P1,F) DAP-UREA applicator total fixed cost per acre in dollars_system2
TFCLIQ2 (P2,F) UAN applicators total fixed cost per acre in dollars_system4
TFCLIQ3 (P2,F) UAN applicators total fixed cost per acre in dollars_system1
TFCLIQ4 (P2,F) UAN applicators total fixed cost acre in dollars_system2
TFCANHY3 (P3,F) ANHYDROUS applicators total fixed cost per acre in dollars_system1
TVCMIX1 (P1,F) DAP-UREA applicators total variable cost per ton in dollars_system3
TVCDAP23 (P1,F) DAP applicators total variable cost per ton in dollars_system1&4
TVCMIX4 (P1,F) DAP-UREA applicators total variable cost per ton in dollars_system2
TVCLIQ2 (P2,F) UAN applicators total variable cost per ton in dollars_system4
TVCLIQ3 (P2,F) UAN applicators total variable cost per ton in dollars_system1
TVCLIQ4 (P2,F) UAN applicators total variable cost per ton in dollars_system2;
TFCMIX1 (P1,F)=MIDCOST1(P1,F)+MIICOST1(P1,F)+MIINCOST1(P1,F);
TFCDAP23 (P1,F)= DADCOST23(P1,F)+DAICOST23 (P1,F)+DAINCOST23(P1,F);
TFCMIX4 (P1,F)=MIDCOST4(P1,F)+MIICOST4(P1,F)+MIINCOST4(P1,F);
TFCLIQ2 (P2,F)=LIDCOST2(P2,F)+LIICOST2(P2,F)+LIINCOST2(P2,F);
TFCLIQ3 (P2,F)=LIDCOST3(P2,F)+LIICOST3(P2,F)+LIINCOST3(P2,F);
TFCLIQ4 (P2,F)=LIDCOST4(P2,F)+LIICOST4(P2,F)+LIINCOST4(P2,F);
TFCANHY3 (P3,F)=AHCOSTPT3(P3,F)+ AHISICOS3(P3,F)+AHSINCOS3 (P3,F);
TVCMIX1 (P1,F)=MIFCOST1(P1,F)+MIOCOST1(P1,F)+ MIRCOST1(P1,F)+MILCOST1(P1,F);
TVCDAP23 (P1,F)=DAFCOST23(P1,F)+ DAOCOST23(P1,F)+DARCOST23(P1,F)+DALCOST23 (P1,F);
TVCMIX4 (P1,F)=MIFCOST4(P1,F)+MIOCOST4(P1,F)+ MIRCOST4(P1,F)+MILCOST4(P1,F);
TVCLIQ2 (P2,F)=LIFCOST2(P2,F)+LIOCOST2(P2,F)+ LIRCOST2(P2,F)+LILCOST2(P2,F);
TVCLIQ3 (P2,F)=LIFCOST3(P2,F)+LIOCOST3(P2,F)+ LIRCOST3(P2,F)+LILCOST3(P2,F);
TVCLIQ4 (P2,F)=LIFCOST4(P2,F)+LIOCOST4(P2,F)+ LIRCOST4(P2,F)+LILCOST4(P2,F);
```

```
 TABLE AREADRY (A1,F) DAP-UREA application area by fields and applicators
                Big-King Big-Okar  Big-Yuko Big-Omeg Big-Pied  Big-Wato Big-Henn
DAPUR-CKing     43119.2    36567.2 30639.2   16026.4   13198.4  13803.2  14586.4
DAPUR-King      43119.2    36567.2 30639.2   16026.4   13198.4  13803.2  14586.4
DAPUR-Okar      43119.2    36567.2 30639.2   16026.4   13198.4  13803.2  14586.4
DAPUR-Yuko      43119.2    36567.2 30639.2   16026.4   13198.4  13803.2  14586.4
DAPUR-Omeg      43119.2    36567.2 30639.2   16026.4   13198.4  13803.2  14586.4
DAPUR-Pied      43119.2    36567.2 30639.2   16026.4   13198.4  13803.2  14586.4
DAPUR-Wato      43119.2    36567.2 30639.2   16026.4   13198.4  13803.2  14586.4
DAPUR-Henn      43119.2    36567.2 30639.2   16026.4   13198.4  13803.2  14586.4
+               Small-King Small-Okar Small-Yuko Small-Omeg Small-Pied Small-Wato Small-Henn
DAPUR-CKing       10779.8  9141.8      7659.8      4006.6     3299.6      3450.8      3646.6
DAPUR-King        10779.8  9141.8      7659.8      4006.6     3299.6      3450.8      3646.6
DAPUR-Okar        10779.8  9141.8      7659.8      4006.6     3299.6      3450.8      3646.6
DAPUR-Yuko        10779.8  9141.8      7659.8      4006.6     3299.6      3450.8      3646.6
DAPUR-Omeg        10779.8  9141.8      7659.8      4006.6     3299.6      3450.8      3646.6
DAPUR-Pied        10779.8  9141.8      7659.8      4006.6     3299.6      3450.8      3646.6
DAPUR-Wato        10779.8  9141.8      7659.8      4006.6     3299.6      3450.8      3646.6
DAPUR-Henn        10779.8  9141.8      7659.8      4006.6     3299.6      3450.8      3646.6;

TABLE AREALIQ (A2,F) LIQUID  application area by fields and applicators
               Big-King Big-Okar Big-Yuko Big-Omeg Big-Pied Big-Wato Big-Henn
LIQ-CKing      43119.2    36567.2 30639.2   16026.4   13198.4  13803.2  14586.4
LIQ-King       43119.2    36567.2 30639.2   16026.4   13198.4  13803.2  14586.4
LIQ-Okar       43119.2    36567.2 30639.2   16026.4   13198.4  13803.2  14586.4
LIQ-Yuko       43119.2    36567.2 30639.2   16026.4   13198.4  13803.2  14586.4
LIQ-Omeg       43119.2    36567.2 30639.2   16026.4   13198.4  13803.2  14586.4
LIQ-Pied       43119.2    36567.2 30639.2   16026.4   13198.4  13803.2  14586.4
LIQ-Wato       43119.2    36567.2 30639.2   16026.4   13198.4  13803.2  14586.4
LIQ-Henn       43119.2    36567.2 30639.2   16026.4   13198.4  13803.2  14586.4
+              Small-King Small-Okar Small-Yuko Small-Omeg Small-Pied Small-Wato Small-Henn
LIQ-CKing       10779.8   9141.8      7659.8      4006.6     3299.6      3450.8      3646.6
LIQ-King        10779.8   9141.8      7659.8      4006.6     3299.6      3450.8      3646.6
LIQ-Okar        10779.8   9141.8      7659.8      4006.6     3299.6      3450.8      3646.6
LIQ-Yuko        10779.8   9141.8      7659.8      4006.6     3299.6      3450.8      3646.6
LIQ-Omeg        10779.8   9141.8      7659.8      4006.6     3299.6      3450.8      3646.6
LIQ-Pied        10779.8   9141.8      7659.8      4006.6     3299.6      3450.8      3646.6
LIQ-Wato        10779.8   9141.8      7659.8      4006.6     3299.6      3450.8      3646.6
LIQ-Henn        10779.8   9141.8      7659.8      4006.6     3299.6      3450.8      3646.6;
```

```
TABLE AREAANHY (A3,F) ANHYDROUS application area by fields and applicators
             Big-King Big-Okar Big-Yuko Big-Omeg Big-Pied  Big-Wato Big-Henn
Sanh-CKing    43119.2  36567.2 30639.2  16026.4  13198.4  13803.2  14586.4
Sanh-King     43119.2  36567.2 30639.2  16026.4  13198.4  13803.2  14586.4
Sanh-Okar     43119.2  36567.2 30639.2  16026.4  13198.4  13803.2  14586.4
Sanh-Yuko     43119.2  36567.2 30639.2  16026.4  13198.4  13803.2  14586.4
Sanh-Omeg     43119.2  36567.2 30639.2  16026.4  13198.4  13803.2  14586.4
Sanh-Pied     43119.2  36567.2 30639.2  16026.4  13198.4  13803.2  14586.4
Sanh-Wato     43119.2  36567.2 30639.2  16026.4  13198.4  13803.2  14586.4
Sanh-Henn     43119.2  36567.2 30639.2  16026.4  13198.4  13803.2  14586.4
Banh-CKing    43119.2  36567.2 30639.2  16026.4  13198.4  13803.2  14586.4
Banh-King     43119.2  36567.2 30639.2  16026.4  13198.4  13803.2  14586.4
Banh-Okar     43119.2  36567.2 30639.2  16026.4  13198.4  13803.2  14586.4
Banh-Yuko     43119.2  36567.2 30639.2  16026.4  13198.4  13803.2  14586.4
Banh-Omeg     43119.2  36567.2 30639.2  16026.4  13198.4  13803.2  14586.4
Banh-Pied     43119.2  36567.2 30639.2  16026.4  13198.4  13803.2  14586.4
Banh-Wato     43119.2  36567.2 30639.2  16026.4  13198.4  13803.2  14586.4
Banh-Henn     43119.2  36567.2 30639.2  16026.4  13198.4  13803.2  14586.4
+            Small-King Small-Okar Small-Yuko Small-Omeg Small-Pied Small-Wato Small-Henn
Sanh-CKing     10779.8   9141.8      7659.8      4006.6    3299.6      3450.8      3646.6
Sanh-King      10779.8   9141.8      7659.8      4006.6    3299.6      3450.8      3646.6
Sanh-Okar      10779.8   9141.8      7659.8      4006.6    3299.6      3450.8      3646.6
Sanh-Yuko      10779.8   9141.8      7659.8      4006.6    3299.6      3450.8      3646.6
Sanh-Omeg      10779.8   9141.8      7659.8      4006.6    3299.6      3450.8      3646.6
Sanh-Pied      10779.8   9141.8      7659.8      4006.6    3299.6      3450.8      3646.6
Sanh-Wato      10779.8   9141.8      7659.8      4006.6    3299.6      3450.8      3646.6
Sanh-Henn      10779.8   9141.8      7659.8      4006.6    3299.6      3450.8      3646.6
Banh-CKing     10779.8   9141.8      7659.8      4006.6    3299.6      3450.8      3646.6
Banh-King      10779.8   9141.8      7659.8      4006.6    3299.6      3450.8      3646.6
Banh-Okar      10779.8   9141.8      7659.8      4006.6    3299.6      3450.8      3646.6
Banh-Yuko      10779.8   9141.8      7659.8      4006.6    3299.6      3450.8      3646.6
Banh-Omeg      10779.8   9141.8      7659.8      4006.6    3299.6      3450.8      3646.6
Banh-Pied      10779.8   9141.8      7659.8      4006.6    3299.6      3450.8      3646.6
Banh-Wato      10779.8   9141.8      7659.8      4006.6    3299.6      3450.8      3646.6
Banh-Henn      10779.8   9141.8      7659.8      4006.6    3299.6      3450.8      3646.6;

Parameters
MIFICOST1 (P1) DAP-UREA applicator fixed cost per applicator_system3
DAFICOST23(P1) DAP applicator fixed cost per applicator_system1&4
MIFICOST4 (P1) DAP-UREA applicator fixed cost per applicator_system2
LIFICOST2 (P2) UAN applicator fixed cost per applicator_system4
LIFICOST3 (P2) UAN applicator fixed cost per applicator_system1
LIFICOST4 (P2) UAN applicator fixed cost per applicator_system2
ANSFCOST3(P3) ANHYDROUS applicator fixed cost per applicator_system1;
MIFICOST1(P1)=(SUM(F,TFCMIX1(P1,F))/14)*84*AWHPY1;
DAFICOST23(P1)=(SUM(F,TFCDAP23(P1,F))/14)*84*AWHPY1;
MIFICOST4(P1)=(SUM(F,TFCMIX4(P1,F))/14)*84*AWHPY1;
LIFICOST2(P2)=(SUM(F,TFCLIQ2(P2,F))/14)*120*AWHPY2;
LIFICOST3(P2)=(SUM(F,TFCLIQ3(P2,F))/14)*120*AWHPY2;
LIFICOST4(P2)=(SUM(F,TFCLIQ4(P2,F))/14)*120*AWHPY2;
ANSFCOST3(P3)=(SUM(F,TFCANHY3(P3,F))/14)*0.445*ANHYWHPY;
```

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*********************************************************************
***ESTIMATION OF APPLICATOR TRANSPORT AND TOTAL APPLICATION  COST ***
*********************************************************************
Table FCOSTNH3 (A3,F) Farmers' cost for applying ANHYDROUS ammonia in dollars per acre
             Big-King Big-Okar Big-Yuko Big-Omeg Big-Pied Big-Wato Big-Henn
Sanh-CKing     5.82     5.82     5.82     5.82     5.82     5.82     5.82
Sanh-King      5.82     5.82     5.82     5.82     5.82     5.82     5.82
Sanh-Okar      5.82     5.82     5.82     5.82     5.82     5.82     5.82
Sanh-Yuko      5.82     5.82     5.82     5.82     5.82     5.82     5.82
Sanh-Omeg      5.82     5.82     5.82     5.82     5.82     5.82     5.820
Sanh-Pied      5.82     5.82     5.82     5.82     5.82     5.82     5.82
Sanh-Wato      5.82     5.82     5.82     5.82     5.82     5.82     5.82
Sanh-Henn      5.82     5.82     5.82     5.82     5.82     5.82     5.82
Banh-CKing     5.82     5.82     5.82     5.82     5.82     5.82     5.82
Banh-King      5.82     5.82     5.82     5.82     5.82     5.82     5.82
Banh-Okar      5.82     5.82     5.82     5.82     5.82     5.82     5.82
Banh-Yuko      5.82     5.82     5.82     5.82     5.82     5.82     5.82
Banh-Omeg      5.82     5.82     5.82     5.82     5.82     5.82     5.82
Banh-Pied      5.82     5.82     5.82     5.82     5.82     5.82     5.82
Banh-Wato      5.82     5.82     5.82     5.82     5.82     5.82     5.82
Banh-Henn      5.82     5.82     5.82     5.82     5.82     5.82     5.82

+            Small-King Small-Okar Small-Yuko Small-Omeg Small-Pied Small-Wato Small-Henn
Sanh-CKing     5.82       5.82       5.82       5.82       5.82       5.82       5.82
Sanh-King      5.82       5.82       5.82       5.82       5.82       5.82       5.82
Sanh-Okar      5.82       5.82       5.82       5.82       5.82       5.82       5.82
Sanh-Yuko      5.82       5.82       5.82       5.82       5.82       5.82       5.82
Sanh-Omeg      5.82       5.82       5.82       5.82       5.82       5.82       5.82
Sanh-Pied      5.82       5.82       5.82       5.82       5.82       5.82       5.82
Sanh-Wato      5.82       5.82       5.82       5.82       5.82       5.82       5.82
Sanh-Henn      5.82       5.82       5.82       5.82       5.82       5.82       5.82
Banh-CKing     5.82       5.82       5.82       5.82       5.82       5.82       5.82
Banh-King      5.82       5.82       5.82       5.82       5.82       5.82       5.82
Banh-Okar      5.82       5.82       5.82       5.82       5.82       5.82       5.82
Banh-Yuko      5.82       5.82       5.82       5.82       5.82       5.82       5.82
Banh-Omeg      5.82       5.82       5.82       5.82       5.82       5.82       5.82
Banh-Pied      5.82       5.82       5.82       5.82       5.82       5.82       5.82
Banh-Wato      5.82       5.82       5.82       5.82       5.82       5.82       5.82
Banh-Henn      5.82       5.82       5.82       5.82       5.82       5.82       5.82;
*Source: Doye, Sahs, and Kletke

Scalars
RMCOST Applicators' repair and maintenance cost per hour in dollars /0.47/
**************************************************************************
**RMCOST is adopted from Dahl et al 1995, it is year 2002 equivalence of $ 0.37**
**    in 1995.                                                          **
**************************************************************************

SFCRA2 Fuel consumption rate for trucks used to ship anhydrous applicators in miles per
gallon /15/;
*Source: Kenkel (Personal Communication)

Parameters
MIXFSCOST(P1,F) Fuel cost for transporting DAP-UREA applicators
LIQFSCOST(P2,F) Fuel cost for transporting UAN applicators
AHDSFCOST  (P3,F) Fuel cost for transporting ANHYDROUS applicators
MIXRSCOST  (P1,F) Repair and maintenance cost for shipping  DAP-UREA applicators
LIQRSCOST  (P2,F) Repair and maintenance cost for shipping  UAN applicators
MIXOSCOST  (P1,F) Oil cost for shipping DAP-UREA applicators
LIQOSCOST  (P2,F) Oil cost for shipping UAN applicators
AHDSOCOST  (P3,F) Oil cost for transporting ANHYDROUS applicators
MIXRTCOST  (P1,F) DAP-UREA applicator round trip shipping cost
LIQRTCOST  (P2,F) UAN applicator round trip shipping cost
AHDSRTCOS  (P3,F) ANHYDROUS round trip shipping cost;
MIXFSCOST(P1,F)=SFCRA*ATFP*TIMEDAPUR(P1,F);
LIQFSCOST(P2,F)=SFCRA*ATFP*TIMELIQ(P2,F);
AHDSFCOST  (P3,F)=(DISTANYD (P3,F)/SFCRA2)*ATFP;
MIXRSCOST  (P1,F)=RMCOST*TIMEDAPUR(P1,F);
LIQRSCOST  (P2,F)=RMCOST*TIMELIQ(P2,F);
MIXOSCOST  (P1,F)=0.15*MIXFSCOST(P1,F);
LIQOSCOST  (P2,F)=0.15*LIQFSCOST(P2,F);
```

```
AHDSOCOST(P3,F)=0.15*AHDSFCOST (P3,F);
MIXRTCOST (P1,F)=2*(MIXFSCOST(P1,F)+MIXRSCOST(P1,F)+MIXOSCOST (P1,F));
LIQRTCOST (P2,F)=2*(LIQFSCOST(P2,F)+LIQRSCOST(P2,F)+LIQOSCOST (P2,F));
AHDSRTCOS (P3,F)=2*(AHDSFCOST (P3,F)+AHDSOCOST (P3,F));

Parameter
MITCPT1 (P1,F) DAP-UREA applicator travel cost per ton of  applied at field_system3
DATCPT23 (P1,F) DAP applicator travel cost per ton of  applied at field_system1&4
MITCPT4 (P1,F) DAP-UREA applicator travel cost per ton of  applied at field_system2
LITCPT2 (P2,F) UAN applicator travel cost per ton of applied at field f_system4
LITCPT3 (P2,F) UAN applicator travel cost per ton of applied at field f_system1
LITCPT4 (P2,F) UAN applicator travel cost per ton of applied at field f_system2
ANSTCPT3 (P3,F) ANHYDROUS applicator travel cost per ton of applied at field f_system1
MITACOST1 (P1,F) DAP-UREA fertilizer total application cost per ton_system3
DAACOST23 (P1,F) DAP fertilizer total application cost per ton_system1&4
MITACOST4 (P1,F) DAP-UREA fertilizer total application cost per ton_system2
LITACOST2 (P2,F) UAN fertilizer total application cost per ton_system4
LITACOST3 (P2,F) UAN fertilizer total application cost per ton_system1
LITACOST4 (P2,F) UAN fertilizer total application cost per ton_system2
AHTACOS3 (P3,F) ANYDROUS AMMONIA total application cost per ton-system1;
MITCPT1 (P1,F)=MIXRTCOST(P1,F)/DAPURCAP1(P1,F);
DATCPT23 (P1,F)=MIXRTCOST(P1,F)/DAPCAP23 (P1,F);
MITCPT4 (P1,F)=MIXRTCOST(P1,F)/DAPURCAP4(P1,F);
LITCPT2 (P2,F)=LIQRTCOST(P2,F)/LIQCAP2(P2,F);
LITCPT3 (P2,F)=LIQRTCOST(P2,F)/LIQCAP3(P2,F);
LITCPT4 (P2,F)=LIQRTCOST(P2,F)/LIQCAP4(P2,F);
ANSTCPT3 (P3,F)=AHDSRTCOS (P3,F)/ANHYDCAP3 (P3,F);
MITACOST1 (P1,F)=MITCPT1(P1,F)+TVCMIX1(P1,F);
DAACOST23(P1,F)=DATCPT23 (P1,F)+TVCDAP23 (P1,F);
MITACOST4 (P1,F)=MITCPT4(P1,F)+TVCMIX4(P1,F);
LITACOST2 (P2,F)=LITCPT2(P2,F)+TVCLIQ2(P2,F);
LITACOST3 (P2,F)=LITCPT3(P2,F)+TVCLIQ3(P2,F);
LITACOST4 (P2,F)=LITCPT4(P2,F)+TVCLIQ4(P2,F);
AHTACOS3 (P3,F) = ANSTCPT3(P3,F)+(FCOSTNH3 (P3,F)/RATEANH3);

****************************************************************************************
** Farmer cost for applying NH3 was assumed to be $ 5.82 (Doye, Sahs and Kletke)      **
** Repair and maintenance cost for shipping anhydrous applicators is assumed to be    **
** negligible.                                                                        **
** Costs are in dollars per acre, dividing it by application rate (tons per acre)     **
** gives costs per ton of fertilizer applied.                                         **
****************************************************************************************

******************************************************************************
**ESTIMATION OF DEMAND FOR NITROGEN (N) AND PHOSPHATE (P2O5) AT THE FIELD LEVEL**
******************************************************************************

Parameters
TFAREA (F) Application area by farm sizes and locations in acres
 /
 Big-King      43119.2
 Big-Okar      36567.2
 Big-Yuko      30639.2
 Big-Omeg      16026.4
 Big-Pied      13198.4
 Big-Wato      13803.2
 Big-Henn      14586.4
 Small-King    10779.8
 Small-Okar    9141.8
 Small-Yuko    7659.8
 Small-Omeg    4006.6
 Small-Pied    3299.6
 Small-Wato    3450.8
 Small-Henn    3646.6/

DEMANDAP (F) Total seasonal demand for DAP At the fields in tons_all systems
DEMAUR1 (F) Total seasonal demand for UREA at the fields in tons_system3
DEMAUR4 (F) Total seasonal demand for UREA at the fields in tons_system2
DEMLIQ2 (F) Total seasonal demand for UAN at the fields in tons_system4
DEMLIQ3 (F) Total seasonal demand for UAN at the fields in tons_system1
DEMLIQ4 (F) Total seasonal demand for UAN at the fields in tons_system2
```

```
DEMANH3 (F) Total seasonal demand for ANHYDROUS AMMONIA at the fields in tons_system1;
DEMANDAP(F)= RATEDAP*TFAREA (F);
DEMAUR1  (F)=RATEURE1*TFAREA (F);
DEMAUR4  (F)=RATEURE4*TFAREA (F);
DEMLIQ2(F)=RATLIQ2*TFAREA (F);
DEMLIQ3(F)=RATLIQ3*TFAREA (F);
DEMLIQ4(F)=RATLIQ4*TFAREA (F);
DEMANH3(F)=RATEANH3*TFAREA (F);

DISPLAY DEMANDAP, DEMAUR1,  DEMAUR4, DEMLIQ2, DEMLIQ3, DEMLIQ4
DEMANH3;

Scalar TAPAREA Total application Area;
TAPAREA=SUM(F, TFAREA (F));

DISPLAY TAPAREA;

***********************************************************************
**ESTIMATION OF DAP and UREA TRANSPORT COSTS FROM SOURCES TO WAREHOUSES*
***********************************************************************

TABLE  DISTDsTw (S1,W) distances from sources of DAP to warehouses
           CKing       King     Okar     Yuko   Omeg   Pied   Wato    Henn
ENID        40.3       40.4     48.4    72.30  52.93  61.90  66.49   20.95
PCTOOSA     151.32     151.42   142.40 135.47 166.33 129.26 186.53  150.15;

Scalars
DAPEN DAP trucking costper ton from Enid to Kingfisher /7/
DAPTOOSA trucking cost per ton from Port of Catoosa to Kingfisher /12/
ANYDCOST  trucking cost per ton from Woodward to Kingfisher /13/;

Parameter
DAPENID (S1,W) DAP trucking cost per ton per mile from Enid
DAPTOOS (S1,W) DAP trucking cost per ton per mile from Port of Catoosa;
DAPENID ("ENID","King")= DAPEN/DISTDsTw("ENID","King");
DAPTOOS ("PCTOOSA","King")=DAPTOOSA/DISTDsTw("PCTOOSA","King");
DISPLAY DAPENID,DAPTOOS;

TABLE  TCOST(S1,W) DAP transfer cost per ton per mile from Sources to warehouses
         CKing       King    Okar     Yuko       Omeg      Pied      Wato       Henn
ENID     0.174       0.178   0.174    0.174       0.174     0.174     0.174      0.174
PCTOOSA  0.079       0.079   0.079    0.079       0.079     0.079     0.079      0.079;

Parameter
TRCOST(S1,W) DAP transfer cost per ton from Sources to warehouses;
TRCOST(S1,W)=TCOST(S1,W)* DISTDsTw (S1,W);

TABLE  DISTUsTw (S2,W) distances from sources of UREA to warehouses
          CKing       King     Okar     Yuko   Omeg   Pied   Wato    Henn
PCTOOSA     151.32     151.42   142.40 135.47 166.33 129.26 186.53  150.15;

TABLE TCOSTU(S2,W)  UREA transfer cost per ton per mile from Sources to warehouses
         CKing       King    Okar     Yuko       Omeg      Pied      Wato       Henn
PCTOOSA  0.079       0.079   0.079    0.079       0.079     0.079     0.079      0.079;

TABLE  DISTLsTw (S3,W) distances from source of UAN to warehouses
          CKing       King     Okar     Yuko   Omeg   Pied   Wato    Henn
ENID        40.3       40.4     48.4    72.30  52.93  61.90  66.49   20.95 ;

TABLE  TCOSTL(S3,W) LIQUID transfer cost per ton per mile from Source to warehouses

         CKing       King    Okar     Yuko       Omeg      Pied      Wato       Henn
ENID     0.174       0.174   0.174    0.174       0.174     0.174     0.174      0.174;

TABLE  DISANYsTw (S4,W) distances from source of ANHYDROUS to warehouses
          CKing       King     Okar     Yuko   Omeg   Pied   Wato    Henn
ENID        40.3      40.4      48.4    72.30  52.93  61.90  66.49   20.95
W-WARD     102.6      102.7     108.9   130.3  89.4   139.6  75.9    109.0;
```

```
Parameter
ANYDTR (S4,W) anhydrous transfer cost per ton from Woodward to Kingfisher;
ANYDTR ("W-WARD","King")= ANYDCOST/DISANYsTw("W-WARD","King");

DISPLAY ANYDTR;

TABLE  TCOSANY(S4,W) ANYDROUS transfer cost per ton per mile from Source to warehouses

          CKing       King    Okar    Yuko      Omeg      Pied      Wato       Henn
ENID      0.174       0.174   0.174   0.174      0.174    0.174     0.174      0.174
W-WARD    0.127       0.127   0.127   0.127      0.127    0.127     0.127      0.127 ;

Parameter
TRCOSTU(S2,W) UREA transfer cost per ton from Sources to warehouses
TRCOSTL(S3,W) UAN transfer cost per ton from Sources to warehouses
TRANHY  (S4,W) ANHYDROUS transfer cost per ton from sources to wsrehouses;
TRCOSTU(S2,W)=TCOSTU(S2,W)* DISTUsTw (S2,W);
TRCOSTL(S3,W)=TCOSTL(S3,W)* DISTLsTw (S3,W);
TRANHY  (S4,W)=DISANYsTw  (S4,W)* TCOSANY(S4,W);

Parameter
CAPWD (W)  Ideal dry storage capacity for a central warehouse in tons
/CKing        20000
 King          4000
 Okar          4000
 Yuko          4000
 Omeg          4000
 Pied          4000
 Wato          4000
 Henn          4000/

CAPWL  (W)  Ideal UAN storage capacity for a central warehouse in tons
/CKing       10000
 King          4000
 Okar          4000
 Yuko          4000
 Omeg          4000
 Pied          4000
 Wato          4000
 Henn          4000/

CAPWANH(W) Ideal anhydrous storage capacity for a central warehouse in tons
/CKing          3000
 King           3000
 Okar           3000
 Yuko           3000
 Omeg           3000
 Pied           3000
 Wato           3000
 Henn           3000/;


Parameter
COST1  (W)  Fixed cost for ownership of dry storage per year in dollars
/CKing       12249.77
 King        7000
 Okar        7000
 Yuko        7000
 Omeg        7000
 Pied        7000
 Wato        7000
 Henn        7000/
```

```
COST2 (W) Fixed cost for ownership of UAN storage per year in dollars
/CKing    6999.87
 King       8000
 Okar       8000
 Yuko       8000
 Omeg       8000
 Pied       8000
 Wato       8000
 Henn       8000/

COST3 (W) Fixed cost for ownership of anhydrous storage per year in dollars
/CKing        576.9231
 King         576.9231
 Okar         576.9231
 Yuko         576.9231
 Omeg         576.9231
 Pied         576.9231
 Wato         576.9231
 Henn         576.9231 /

OPCOST1(W) Opportunity cost of funds used to acquire dry storage in dollars per year
OPCOST2(W) Opportunity cost of funds used to acquire UAN storage in dollars per year
OPCOST3(W) Opportunity cost of funds used to acquire anhydrous dry storage in dollars per
year
PVINTX1 (W) Property value insurance and tax for dry storage
PVINTX2 (W) Property value insurance and tax for UAN storage
PVINTX3 (W) Property value insurance and tax for anhydrous storage
MAINCOST1 (W) Maintenance cost for dry storage
MAINCOST2 (W) Maintenance cost for UAN storage
MAINCOST3 (W) Maintenance cost for anhydrous storage
FWCOST1 (W) Total cost for dry warehousing per year in dollars
FWCOST2 (W) Total cost for UAN warehousing per year in dollars
FWCOST3 (W) Total cost for anhydrous warehousing per year in dollars;
OPCOST1(W)=(0.5*COST1(W)*0.08);
OPCOST2(W)=(0.5*COST2(W)*0.08);
OPCOST3(W)=(0.5*COST3(W)*0.08);
PVINTX1 (W)=COST1(W)*0.025*40 ;
PVINTX2 (W)=COST2(W)*0.025*40;
PVINTX3 (W)=COST3(W)*0.025*40;
MAINCOST1 (W)=COST1(W)*0.03*40;
MAINCOST2 (W)=COST2(W)*0.03*40;
MAINCOST3 (W)=COST3(W)*0.03*40;
FWCOST1 (W)= COST1(W)+OPCOST1(W)+PVINTX1(W)+MAINCOST1(W);
FWCOST2 (W)= COST2(W)+OPCOST2(W)+PVINTX2(W)+MAINCOST2(W);
FWCOST3 (W)= COST3(W)+OPCOST3(W)+PVINTX3(W)+MAINCOST3(W);
DISPLAY FWCOST1, FWCOST2, FWCOST3;

Parameter
JJ1(W) Per ton costs for dry warehouses
JJ2(W) Per ton costs for UAN warehouses
JJ3 (W) Per ton costs for ANHYDROUS warehouses;
JJ1(W)= FWCOST1 (W)/CAPWD (W);
JJ2(W)= FWCOST2 (W)/CAPWL (W);
JJ3(W)= FWCOST3 (W)/CAPWANH (W);
```

```
****************************************************************************
**ESTIMATION OF TRUCKING COST: TENDER TRUCKS ARE USED TO SHIP FERTILIZERS***
**FROM WARE HOUSES TO FIELDS                                             ***
****************************************************************************
TABLE TRUDIST (W,F) Truck travel distance from warehouses to fields in miles
        Big-King Big-Okar Big-Yuko Big-Omeg Big-Pied Big-Wato Big-Henn
CKing    5        9.70     32.67    27.30    30.20    40.50    29.70
King     5        9.70     32.67    27.30    30.20    40.50    29.70
Okar     9.70     5.00     28.40    30.60    26.00    43.80    33.00
Yuko     32.6     28.40    5        53.50    16.50    57.50    55.90
Omeg     27.3     30.60    53.50    5        43.50    18.20    38.80
Pied     30.20    26.00    16.50    43.50    5        56.70    45.90
Wato     40.50    43.80    57.50    18.20    56.70    5        52.00
Henn     29.70    33.00    55.90    38.80    45.90    52.00    5
+        Small-King Small-Okar Small-Yuko Small-Omeg Small-Pied Small-Wato Small-Henn
CKing    5          9.70       32.67      27.30      30.20        40.50      29.70
King     5          9.70       32.67      27.30      30.20        40.50      29.70
Okar     9.70       5.00       28.40      30.60      26.00        43.80      33.00
Yuko     32.6       28.40      5          53.50      16.50        57.50      55.90
Omeg     27.3       30.60      53.50      5          43.50        18.20      38.80
Pied     30.20      26.00      16.50      43.50      5            56.70      45.90
Wato     40.50      43.80      57.50      18.20      56.70        5          52.00
Henn     29.70      33.00      55.90      38.80      45.90        52.00      5;

Scalars
SFCRATE Standard fuel consumption rate for diesel ignited truck in miles per gallon /7.5/
FuelTR20 Fuel consumption rate for 20-ton truck in mpg per ton
TDCOSTM 20 ton truck diesel cost per mile
TOCOSTM 20 ton truck oil cost per mile in dollars
TRMCOSTM 20 ton truck repair and maintenance cost per mile in dollars per ton /0.0025/
*****************************************************************
*TRMCOSTM value is a year 2002 equivalence of $ 0.035 in 1995.***
*****************************************************************
TIRCOSTM 20 ton tires cost per mile per ton in dollars /0.0015/
************************************************************
* Similarly TIRCOSTM is inflated from its 1995 equivalence**
************************************************************
TTCOSTM Total Trucking cost per mile per ton;
FuelTR20= SFCRATE/20;
TDCOSTM=FuelTR20*ATFP;
TOCOSTM=0.15*TDCOSTM;
TTCOSTM=FuelTR20+TOCOSTM+TRMCOSTM +TIRCOSTM;
Display TTCOSTM;
*********************************************************************
*Values used in the estimation are adopted from Dahl et al (1995).**
*********************************************************************


Parameter
TTRUCOST (W,F) Total trucking cost for shipping DAP or UREA or UAN or ANYDROUS from
warehouses
               to fields in dollars per ton;
TTRUCOST (W,F)= 2*TRUDIST (W,F)*TTCOSTM;

DISPLAY TTRUCOST;

VARIABLES
X111(S1,W) tons of DAP shipped from S1 to warehouse W_system3
X112(S1,W) tons of DAP shipped from S1 to warehouse W_system4
X113(S1,W) tons of DAP shipped from S1 to warehouse W_system1
X114(S1,W) tons of DAP shipped from S1 to warehouse W_system2
X121(S2,W) tons of UREA shipped from S2 to warehouse W_system3
X124(S2,W) tons of UREA shipped from S2 to warehouse W_system2
X132(S3,W) tons of LIQUID ammonia shipped from S3 to warehouse W_system4
X133(S3,W) tons of LIQUID ammonia shipped from S3 to warehouse W_system1
X134(S3,W) tons of LIQUID ammonia shipped from S3 to warehouse W_system2
X143(S4,W) tons of ANHYDROUS ammonia shipped from S4 to warehouse W_system1
X211(W,F) tons of DAP shipped from warehouse to fields_system3
X212(W,F) tons of DAP shipped from warehouse to fields_system4
X213(W,F) tons of DAP shipped from warehouse to fields_system1
X214(W,F) tons of DAP shipped from warehouse to fields_system2
X221(W,F) tons of UREA shipped from warehouse to fields_system3
```

```
X224(W,F) tons of UREA shipped from warehouse to fields_system2
X232(W,F) tons of UAN shipped from warehouse to fields_system4
X233(W,F) tons of UAN shipped from warehouse to fields_system1
X234(W,F) tons of UAN shipped from warehouse to fields_system2
X243(W,F) tons of ANHYDROUS shipped from warehouse to fields_system1
X311(P1,F) tons of DAP and UREA applied at field F using applicator A1_system3
X312(P1,F) tons of DAP applied at field F using applicator A1_system4
X313(P1,F) tons of DAP applied at field F using applicator A1_system1
X314(P1,F) tons of DAP and UREA applied at field F using applicator A1_system2
X322(P2,F) tons of UAN applied at field F using applicator A2_system4
X323(P2,F) tons of UAN applied at field F using applicator A2_system1
X324(P2,F) tons of UAN applied at field F using applicator A2_system2
X333 (P3,F) tons of anhydrous ammonia applied at field F using applicator A3_system1
X411(W) Binary variable for construction of DAP-UREA warehouse_system3
X412(W) Binary variable for construction of DAP warehouse_system4
X413(W) Binary variable for construction of DAP warehouse_system1
X414(W) Binary variable for construction of DAP-UREA warehouse_system2
X422(W) Binary variable for the construction of UAN warehouse_system4
X423(W) Binary variable for the construction of UAN warehouse_system1
X424(W) Binary variable for the construction of UAN warehouse_system2
X433(W) Binary variable for the construction of ANHYDROUS warehouse_system1
**************************************************************************************
*X411 (W),…, X433(W) equals to one if construction is feasible, and zero otherwise**
**************************************************************************************
X511(P1) Integer variable for the purchase of dry fertilizer applicators_system3
X512(P1) Integer variable for the purchase of dry fertilizer applicators_system4
X513(P1) Integer variable for the purchase of dry fertilizer applicators_system1
X514(P1) Integer variable for the purchase of dry fertilizer applicators_system2
X522(P2) Integer variable for the purchase of UAN applicators_system4
X523(P2) Integer variable for the purchase of UAN applicators_system1
X524(P2) Integer variable for the purchase of UAN applicators_system2
X533(P3) Integer variable for the purchase of anhydrous fertilizer applicators_system1
*********************************************************************************
*Integer variables ensure purchase of full unit(s) of applicators            ***
*********************************************************************************
Z3 total cost_system3
Z4 total cost_system4
Z1 total cost_system1
Z2 total cost_system2

POSITIVE VARIABLES X111, X112, X113, X114, X121, X124,
X132, X133, X134, X143,X211, X212, X213, X214, X221, X224
X232, X233, X234, X243,X311, X312,X313, X314, X322
X323, X324, X333;
BINARY VARIABLES X411, X412,X413, X414, X422, X423, X424, X433;
INTEGER VARIABLES X511, X512, X513, X514, X522, X523, X524
X533;

EQUATIONS
COST_3 objective function_system3
COST_4 objective function_system4
COST_1 objective function_system1
COST_2 objective function_system2
DAPSUP1(S1) Observe DAP supply constraint at source S1_system3
DAPSUP2(S1) Observe DAP supply constraint at source S1_system4
DAPSUP3(S1) Observe DAP supply constraint at source S1_system1
DAPSUP4(S1) Observe DAP supply constraint at source S1_system2
UREASUP1(S2) Observe UREA supply constraint at source S2_system3
UREASUP4(S2) Observe UREA supply constraint at source S2_system2
LIQSUP2(S3) Observe UAN  supply constraint at source S3_system4
LIQSUP3(S3) Observe UAN  supply constraint at source S3_system1
LIQSUP4(S3) Observe UAN  supply constraint at source S3_system2
ANYSUP3(S4) Observe ANHYDROUS AMMONIA  supply constraint at source S4_system1
DAPDEM1(F) Satisfy DAP-P205 demand at field F_system3
DAPDEM2(F) Satisfy DAP-P205 demand at field F_system4
DAPDEM3(F) Satisfy DAP-P205 demand at field F_system1
DAPDEM4(F) Satisfy DAP-P205 demand at field F_system2
UREADEM1(F) Satisfy UREA-nitrogen demand at field F_system3
UREADEM4(F) Satisfy UREA-nitrogen demand at field F_system2
LIQDEM2 (F) Satisfy UAN-nitrogen demand at field F_system4
LIQDEM3 (F) Satisfy UAN-nitrogen demand at field F_system1
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LIQDEM4  (F) Satisfy UAN-nitrogen demand at field F_system2
ANYDDEM3  (F) Satisfy ANYDROUS-nitrogen demand at field F_system1
APLOCD1(P1)  Choice of DAP-UREA applicator A1 at field F_system3
APLOCD2(P1)  Choice of DAP-UREA applicator A1 at field F_system4
APLOCD3(P1)  Choice of DAP-UREA applicator A1 at field F_system1
APLOCD4(P1)  Choice of DAP applicator A1 at field F_system2
APLOCL2(P2)  Choice of UAN applicator A2 at field F_system4
APLOCL3(P2)  Choice of UAN applicator A2 at field F_system1
APLOCL4(P2)  Choice of UAN applicator A2 at field F_system2
APLOCAN3(P3) Choice of ANYDROUS applicator A3 at field F_system1
CAPACD1(W)  Observe storage capacity for dry fertilizers (DAP and UREA)_system3
CAPACD2(W)  Observe storage capacity for dry fertilizers (DAP only)_system4
CAPACD3(W)  Observe storage capacity for dry fertilizers (DAP only)_system1
CAPACD4(W) Observe storage capacity for dry fertilizers (DAP and UREA)_system2
CAPACL2(W)  Observe warehouse storage capacity for UAN fertilizers_system4
CAPACL3(W)  Observe warehouse storage capacity for UAN fertilizers_system1
CAPACL4(W)  Observe warehouse storage capacity for UAN fertilizers_system2
CAPACAN3(W) Observe warehouse storage capacity for ANHYDROUS fertilizers_system1
DAPBAL1(W)  Observe DAP flow balance_system3
DAPBAL2(W)  Observe DAP flow balance_system4
DAPBAL3(W)  Observe DAP flow balance_system1
DAPBAL4(W)  Observe DAP flow balance_system2
UREABAL1(W) Observe UREA flow balance_system3
UREABAL4(W) Observe UREA flow balance_system2
LIQBAL2(W)  Observe UAN flow balance_system4
LIQBAL3(W)  Observe UAN flow balance_system1
LIQBAL4(W)  Observe UAN flow balance_system2
ANHYBAL3(W) Observe ANHYDROUS flow balance_system1
MIXRATI1(F) Observe DAP and UREA mix ratio_system1
APPLYD2(F)  Observe DRY fertilizer application requirement_system4
APPLYD3(F)  Observe DRY fertilizer application requirement_system1
MIXRATI4(F) Observe DAP and UREA mix ratio_system2
APPLYL2(F)  Observe UAN fertilizer application requirement_system4
APPLYL3(F)  Observe UAN fertilizer application requirement_system1
APPLYL4(F)  Observe UAN fertilizer application requirement_system2
APPLYAN3(F) Observe anhydrous fertilizer application requirement_system1;

COST_3..Z3=E= SUM((S1,W), X111(S1,W)*TRCOST(S1,W))+SUM((S2,W), X121(S2,W)
             *TRCOSTU(S2,W))+SUM((W,F),X211(W,F)*TTRUCOST(W,F))
             +SUM((W,F),X221(W,F)*TTRUCOST(W,F))+SUM((P1,F),MITACOST1 (P1,F)
             *X311(P1,F))+SUM(W,X411(W)*FWCOST1(W))+ SUM(P1,MIFICOST1(P1)*X511(P1));

COST_4..Z4=E=SUM((S1,W), X112(S1,W)*TRCOST(S1,W))+SUM((S3,W), X132(S3,W)*TRCOSTL(S3,W))
             +SUM((W,F),X212(W,F)*TTRUCOST(W,F))+SUM((W,F),X232(W,F)*TTRUCOST(W,F))
             +SUM((P1,F),DAACOST23(P1,F)*X312(P1,F))+SUM((P2,F),LITACOST2(P2,F)
             *X322(P2,F))+ SUM(W,X412(W)*FWCOST1(W))+ SUM(W,X422(W)*FWCOST2(W)) +
              SUM(P1,DAFICOST23(P1)*X512(P1))+SUM(P2,LIFICOST2(P2)*X522(P2));

COST_1..Z1=E=SUM((S1,W), X113(S1,W)*TRCOST(S1,W))+ SUM((S3,W), X133(S3,W)*TRCOSTL(S3,W))
             +SUM((S4,W), X143(S4,W)*TRANHY (S4,W))+SUM((W,F),X213(W,F)*TTRUCOST(W,F))
             +SUM((W,F),X243(W,F)*TTRUCOST(W,F))+SUM((W,F),X233(W,F)*TTRUCOST(W,F))
             +SUM((P1,F),DAACOST23(P1,F)*X313(P1,F))+ SUM((P3,F),AHTACOS3 (P3,F)
             *X333(P3,F))+SUM((P2,F),LITACOST3(P2,F)*X323(P2,F))+SUM(W,X413(W)
             *FWCOST1(W))+SUM(W,X423(W)*FWCOST2(W))+SUM(W,X433(W)*FWCOST3(W))
             +SUM(P1,DAFICOST23(P1)*X513(P1))+SUM(P3, ANSFCOST3(P3)*X533(P3))
             +SUM(P2,LIFICOST3(P2)*X523(P2));

COST_2..Z2=E=SUM((S1,W), X114(S1,W)*TRCOST(S1,W))+SUM((S2,W), X124(S2,W)*TRCOSTU(S2,W))
             +SUM((S3,W), X134(S3,W)*TRCOSTL(S3,W))+SUM((W,F),X214(W,F)*TTRUCOST(W,F))
             +SUM((W,F),X224(W,F)*TTRUCOST(W,F))+SUM((W,F),X234(W,F)*TTRUCOST(W,F))
             +SUM((P1,F),MITACOST4(P1,F)*X314(P1,F))+SUM((P2,F),LITACOST4(P2,F)
             *X324(P2,F))+SUM(W,X414(W)*FWCOST1(W))+SUM(W,X424(W)*FWCOST2(W))
             +SUM(P1,MIFICOST4(P1)*X514(P1))+SUM(P2,LIFICOST4(P2)*X524(P2));

DAPSUP1(S1)..SUM(W, X111(S1,W)) =L=SUPDAP(S1);
DAPSUP2(S1)..SUM(W, X112(S1,W)) =L=SUPDAP(S1);
DAPSUP3(S1)..SUM(W, X113(S1,W)) =L=SUPDAP(S1);
DAPSUP4(S1)..SUM(W, X114(S1,W)) =L=SUPDAP(S1);
UREASUP1(S2)..SUM(W, X121(S2,W)) =L=SUPUREA(S2);
UREASUP4(S2)..SUM(W, X124(S2,W)) =L=SUPUREA(S2);
LIQSUP2(S3)..SUM(W, X132(S3,W))=L=SUPLIQ(S3);
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LIQSUP3(S3)..SUM(W, X133(S3,W))=L=SUPLIQ(S3);
LIQSUP4(S3)..SUM(W, X134(S3,W))=L=SUPLIQ(S3);
ANYSUP3(S4)..SUM(W, X143(S4,W))=L=SUPPANHY (S4);
CAPACD1(W)..SUM(F,X211(W,F))+SUM(F,X221(W,F))=L=X411(W)*CAPWD(W);
CAPACD2(W)..SUM( F,X212(W,F))=L=X412(W)*CAPWD(W);
CAPACD3(W)..SUM(F,X213(W,F))=L=X413(W)*CAPWD(W);
CAPACD4  (W)..SUM(F,X214(W,F))+SUM(F,X224(W,F))=L=X414(W)*CAPWD(W);
CAPACL2(W)..SUM(F,X232(W,F))=L=X422(W)*CAPWL(W);
CAPACL3(W)..SUM(F,X233(W,F))=L=X423(W)*CAPWL(W);
CAPACL4(W)..SUM(F,X234(W,F))=L=X424(W)*CAPWL(W);
CAPACAN3(W)..SUM(F,X243(W,F))=L=X433(W)*CAPWANH(W);
DAPDEM1(F)..SUM(W,X211(W,F))=E=DEMANDAP(F);
DAPDEM2(F)..SUM(W,X212(W,F))=E=DEMANDAP(F);
DAPDEM3(F)..SUM(W,X213(W,F))=E=DEMANDAP(F);
DAPDEM4(F)..SUM(W,X214(W,F))=E=DEMANDAP(F);
LIQDEM2(F)..SUM(P2,X322(P2,F))=E=DEMLIQ2(F);
LIQDEM3(F)..SUM(P2,X323(P2,F))=E=DEMLIQ3(F);
LIQDEM4(F)..SUM(P2,X324(P2,F))=E=DEMLIQ4(F);
UREADEM1(F)..SUM(W,X221(W,F))=E=DEMAUR1(F);
UREADEM4(F)..SUM(W,X224(W,F))=E=DEMAUR4(F);
ANYDDEM3(F)..SUM(P3,X333(P3,F))=E=DEMANH3 (F);
DAPBAL1(W)..SUM(F,X211(W,F))=L=SUM(S1, X111(S1,W));
DAPBAL2(W)..SUM(F,X212(W,F))=L=SUM(S1, X112(S1,W));
DAPBAL3(W)..SUM(F,X213(W,F))=L=SUM(S1, X113(S1,W));
DAPBAL4(W)..SUM(F,X214(W,F))=E=SUM(S1, X114(S1,W));
UREABAL1(W)..SUM(F,X221(W,F))=L=SUM(S2, X121(S2,W));
UREABAL4(W)..SUM(F,X224(W,F))=E=SUM(S2, X124(S2,W));
LIQBAL2(W)..SUM(F,X232(W,F))=L=SUM(S3, X132(S3,W));
LIQBAL3(W)..SUM(F,X233(W,F))=L=SUM(S3, X133(S3,W));
LIQBAL4(W)..SUM(F,X234(W,F))=L=SUM(S3, X134(S3,W));
ANHYBAL3(W)..SUM(F,X243(W,F))=L=SUM(S4, X143(S4,W));
APLOCD1(P1)..SUM(F,X311(P1,F))=L=DAURTCAP1 (P1)*X511(P1);
APLOCD2(P1)..SUM(F,X312(P1,F))=L=DATCAP23(P1)*X512(P1);
APLOCD3(P1)..SUM(F,X313(P1,F))=L=DATCAP23(P1)*X513(P1);
APLOCD4(P1)..SUM(F,X314(P1,F))=L=DAURTCAP4 (P1)*X514(P1);
APLOCL2(P2)..SUM(F,X322(P2,F))=L=LITMCAP2 (P2)*X522(P2);
APLOCL3(P2)..SUM(F,X323(P2,F))=L=LITMCAP3 (P2)*X523(P2);
APLOCL4(P2)..SUM(F,X324(P2,F))=L=LITMCAP4 (P2)*X524(P2);
APLOCAN3(P3)..SUM(F,X333(P3,F))=L=ANTMCAP3(P3) *X533(P3);
APPLYD2(F)..SUM(A1, X312(A1,F))=E=SUM(W,X212(W,F));
APPLYD3(F)..SUM(A1, X313(A1,F))=E=SUM(W,X213(W,F));
MIXRATI1(F)..SUM(W, X211(W,F))+SUM(W,X221(W,F))=E=SUM(P1,X311(P1,F));
MIXRATI4(F)..SUM(W, X214(W,F))+SUM(W,X224(W,F))=E=SUM(P1,X314(P1,F));
APPLYL2(F)..SUM(A2, X322(A2,F))=E=SUM(W,X232(W,F));
APPLYL3(F)..SUM(A2, X323(A2,F))=E=SUM(W,X233(W,F));
APPLYL4(F)..SUM(A2, X324(A2,F))=E=SUM(W,X234(W,F));
APPLYAN3(F)..SUM(A3, X333(A3,F))=E=SUM(W,X243(W,F));

MODEL SYSTEM3/COST_3,DAPSUP1,UREASUP1,CAPACD1,DAPDEM1,UREADEM1,DAPBAL1,UREABAL1,APLOCD1
            MIXRATI1/;

MODEL SYSTEM4/COST_4,DAPSUP2,LIQSUP2,CAPACD2,CAPACL2,DAPDEM2,LIQDEM2,DAPBAL2,LIQBAL2,
            APLOCD2,APPLYD2,APPLYL2,APLOCL2/;

MODEL SYSTEM1/COST_1,DAPSUP3,ANYSUP3,CAPACD3,CAPACAN3,DAPDEM3,ANYDDEM3,DAPBAL3,CAPACL3
            ANHYBAL3,APPLYD3,LIQSUP3,LIQDEM3,LIQBAL3,APPLYL3,APLOCL3,APPLYAN3
            APLOCD3,APLOCAN3/;

MODEL SYSTEM2/COST_2,DAPSUP4,UREASUP4,LIQSUP4,CAPACD4,CAPACL4,DAPDEM4,UREADEM4, DAPBAL4
            LIQDEM4,UREABAL4,LIQBAL4,APLOCD4,APLOCL4,MIXRATI4,APPLYL4/;

SOLVE SYSTEM1 USING MIP MINIMIZING Z1;
SOLVE SYSTEM2 USING MIP MINIMIZING Z2;
SOLVE SYSTEM3 USING MIP MINIMIZING Z3;
SOLVE SYSTEM4 USING MIP MINIMIZING Z4;
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** DETAILED ANALYSIS OF COST STRUCTURE                       **
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Parameter
M1(W) Cost for shipping DAP from sources to warehouses SY3
M2(W) Cost for shipping urea from sources to warehouses SY3
M3(F) Cost for shipping DAP from warehouse to fields SY3
M4(F) Cost for shipping urea from warehouses to fields SY3
M5(F) Cost for applying DAP and urea SY3
M6(W) DAP and urea warehousing cost SY3
M7(P1) DAP and Urea applicator fixed costs SY3
M8(W) Total transportation cost sources warehouses SY3
M9(F) Total transportation cost warehouses to fields SY3
H1(W) Cost for shipping DAP from sources to warehouses SY4
H2(W) Cost for shipping UAN from sources to warehouses SY4
H3(F) Cost for shipping DAP from warehouses to fields SY4
H4(F) Cost for shipping UAN from warehouse to fields SY4
H5(F) Cost for applying DAP SY4
H6(F) Cost for applying UAN SY4
H7(W) DAP warehousing cost SY4
H8(W) UAN warehousing cost SY4
H9(P1) DAP applicator fixed costs SY4
H10(P2) UAN applicator fixed costs SY4
H11(W) Total transportation cost sources warehouses SY4
H12(F) Total transportation cost warehouses to fields SY4
R1(W) Cost for shipping DAP from sources to warehouses SY1
R2(W) Cost for shipping UAN from sources to warehouses SY1
R3(W) Cost for shipping ANHYDROUS from sources to warehouses SY1
R4(F) Cost for shipping DAP from warehouses to fields SY1
R5(F) Cost for shipping UAN from warehouses to fields SY1
R6(F) Cost for shipping ANHYDROUS from warehouse to fields SY1
R7(F) Cost for applying DAP SY1
R8(F) Cost for applying UAN SY1
R9(F) Cost for applying ANHYDROUS SY1
R10 (W) DAP warehousing cost SY1
R11(W) UAN warehousing cost SY1
R12(W) ANHYDROUS warehousing cost SY1
R13 (P1) Fixed costs for DAP applicator SY1
R14 (P2) Fixed costs for UAN applicator SY1
R15 (P3) Fixed costs for ANHDROUS applicator SY1
R16(W) Transportation costs sources to warehouses SY1
R17(F) Transportation costs warehouses to fields SY1
J1(W) Cost for shipping DAP from sources to warehouses SY2
J2(W) Cost for shipping urea from sources to warehouses SY2
J3(W) Cost for shipping UAN from sources to warehouses  SY2
J4(F) Cost for shipping DAP from warehouses to fields  SY2
J5(F) Cost for shipping urea from warehouses to fields SY2
J6(F) Cost for shipping UAN warehouses to fields SY2
J7(F) DAP and urea application cost SY2
J8(F) UAN application cost SY2
J9(W) DAP and urea warehousing cost SY2
J10(W) UAN warehousing cost SY2
J11(P1) DAP and Urea applicator fixed costs SY2
J12(P2) UAN applicator fixed cost SY2
J13(W) shipping cost from sources to warehouses SY2
J14(F) shipping cost from warehouses to fields SY2;

Scalar
M10 Total shipping cost SY3
M11 Total applicator fixed costSY3
M12 Total warehousing cost SY3
M13 Total application cost SY3
M14 Total system cost SY3
H13 Total transportation cost SY4
H14 Total application cost SY4
H15 Total warehousing cost SY4
H16 Total applicator fixed cost SY4
H17 Total system cost SY4
H101 Transportation cost sources to warehouse SY4
H102 Transportation cost warehouses to fields SY4
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 H103 Per acre transportation cost sources to warehouse SY4
 H104 Per acre transportation cost warehouses to sources SY4
 H105 Per acre transportation cost SY4
 H106 Per acre application cost SY4
 H107 Per acre warehousing cost SY4
 H108 Per acre applicator fixed cost SY4
 H109 Per acre total cost SY4
 R18 Total transportation costs SY1
 R19 Total application costs SY1
 R20 Total warehousing costs SY1
 R21 Total applicator fixed costs SY1
 R22 Total system cost SY1
 J15 Total shipping cost SY2
 J16 Total warehousing cost SY2
 J17 Total application cost SY2
 J18 Fixed applicator costs SY2
 J19 Total system costs SY2
 R100 NH3 application cost
 R101 Per acre shipping cost from sources to warehouses SY1
 R102 Per acre shipping cost from warehouses to fields SY1
 R103 Per acre shipping cost SY1
 R104 Per acre application cost SY1
 R105 Per acre warehousing cost SY1
 R106 Per acre applicator cost SY1
 R107 Per acre total cost SY1
 J101 Per acre shipping cost from sources to warehouses SY2
 J102 Per acre shipping cost from warehouses to sources SY2
 J103 Per acre shipping cost SY2
 J104 Per acre warehousing cost SY2
 J105 Per acre application cost SY2
 J106 Per acre applicator fixed cost SY2
 J107 Per acre total cost SY2
 M101 Shipping cost from sources to warehouses SY3
 M102 Shipping cost from warehouses to fields SY3
 M103 Per acre shipping cost from sources to warehouses SY3
 M104 Per acre shipping cost from warehouses to fields SY3
 M105 Per acre shipping cost SY3
 M106 Per acre applicator fixed cost SY3
 M107 Per acre warehousing cost SY3
 M108 Per acre application cost SY3
 M109 Per acre total cost SY3
 TCWS_DAP1 Total cost operating cost for DAP without storage cost
 TCWS_UAN1 Total cost operating cost for UAN without storage cost
 TCWS_ANH1 Total cost operating cost for UAN without storage cost;

R1(W)=SUM(S1, X113.L(S1,W)*TRCOST(S1,W)); R2(W)=SUM(S3, X133.L(S3,W)*TRCOSTL(S3,W));
R3(W)=SUM(S4, X143.L(S4,W)*TRANHY(S4,W)); R4(F)=SUM(W, X213.L(W,F)*TTRUCOST(W,F));
R5(F)=SUM(W, X243.L(W,F)*TTRUCOST(W,F));R6(F)=SUM(W, X233.L(W,F)*TTRUCOST(W,F));
R7(F)=SUM(P1, X313.L(P1,F)*DAACOST23(P1,F)); R8(F)=SUM(P2, X323.L(P2,F)*LITACOST3(P2,F));
R9(F)=SUM(P3, X333.L(P3,F)*AHTACOS3(P3,F)); R10(W)=X413.L(W)*FWCOST1(W);
R11(W)=X423.L(W)*FWCOST2(W); R12(W)=X433.L(W)*FWCOST3(W);
R13(P1)=DAFICOST23(P1)*X513.L(P1); R14(P2)=LIFICOST3(P2)*X523.L(P2);
R15(P3)=ANSFCOST3(P3)*X533.L(P3); R16(W)=R1(W)+R2(W)+R3(W); R17(F)=R4(F)+R5(F)+R6(F);
R18=SUM(W, R16(W))+SUM(F,R17(F)); R19=SUM(F,R7(F))+SUM(F,R8(F))+SUM(F,R9(F));
R20=SUM(W, R10(W))+SUM(W,R11(W))+SUM(W,R12(W));
R21=SUM(P1, R13(P1))+SUM(P2, R14(P2))+SUM(P3,R15(P3));
R22=R18+R19+R20+R21;
R100=SUM(F, R9(F));
R101=SUM(W,R16(W))/TAPAREA; R102=SUM(F,R17(F))/TAPAREA; R103=R18/TAPAREA;
R104=R19/TAPAREA;
R105=R20/TAPAREA; R106=R21/TAPAREA; R107=R22/TAPAREA;
TCWS_DAP1=SUM(W,R1(W))+SUM(F,R4(F))+SUM(F,R7(F));
TCWS_UAN1=SUM(W,R2(W))+SUM(F,R5(F))+SUM(F,R8(F));
TCWS_ANH1=SUM(W,R3(W))+SUM(F,R6(F))+SUM(F,R9(F));

DISPLAY R16, R17, R18, R19, R20, R21, R22, R100, R101, R102, R103, R104
R105, R106, R107, TCWS_DAP1, TCWS_UAN1, TCWS_ANH1;


J1(W)=SUM(S1, X114.L(S1,W)*TRCOST(S1,W)); J2(W)=SUM(S2,X124.L(S2,W)*TRCOSTU(S2,W));
J3(W)=SUM(S3, X134.L(S3,W)*TRCOSTL(S3,W)); J4(F)= SUM(W,X214.L(W,F)*TTRUCOST(W,F));
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J5(F)=SUM(W,X224.L(W,F)*TTRUCOST(W,F)); J6(F)=SUM(W,X234.L(W,F)*TTRUCOST(W,F));
J7(F)=SUM(P1,MITACOST4 (P1,F)*X314.L(P1,F)); J8(F)=SUM(P2,LITACOST4(P2,F)*X324.L(P2,F));
J9(W)=X414.L(W)*FWCOST1(W); J10(W)=X424.L(W)*FWCOST2(W);
J11(P1)=MIFICOST4(P1)*X514.L(P1);
J12(P2)=LIFICOST4(P2)*X524.L(P2); J13(W)=J1(W)+J2(W)+J3(W); J14(F)=J4(F)+J5(F)+J6(F);
J15=SUM(W,J13(W))+SUM(F,J14(F));
J16=SUM(W,J9(W))+SUM(W,J10(W));
J17=SUM(F,J7(F))+SUM(F,J8(F));
J18=SUM(P1,J11(P1))+SUM(P2,J12(P2));
J19=J15+J16+J17+J18;
J101=SUM(W,J13(W))/TAPAREA; J102=SUM(F,J14(F))/TAPAREA; J103=J15/TAPAREA;
J104=J16/TAPAREA;J105= J17/TAPAREA; J106=J18/TAPAREA;
J107=J19/TAPAREA;

DISPLAY J11,J12, J13, J14, J15,J16,J17,J18,J19, J101, J102, J103, J104
J105, J106, J107;

M1(W)=SUM(S1, X111.L(S1,W)*TRCOST(S1,W)); M2(W)=SUM(S2,X121.L(S2,W)*TRCOSTU(S2,W));
M3(F)=SUM(W,X211.L(W,F)*TTRUCOST(W,F));M4(F)=SUM(W,X221.L(W,F)*TTRUCOST(W,F));
M5(F)=SUM(P1,MITACOST1 (P1,F)*X311.L(P1,F));M6(W)=X411.L(W)*FWCOST1(W);
M7(P1)=MIFICOST1(P1)*X511.L(P1); M8(W)=M1(W)+M2(W);M9(F)=M3(F)+M4(F);
M10=SUM(W, M8(W))+SUM(F,M9(F));
M11=SUM(P1,M7(P1));M12=SUM(W,M6(W)); M13=SUM(F,M5(F));
M14=M10+M11+M12+M13;
M101=SUM(W, M8(W));M102=SUM(F,M9(F));
M103=SUM(W, M8(W))/TAPAREA; M104=SUM(F,M9(F))/TAPAREA;
M105=M10/TAPAREA; M106=M11/TAPAREA; M107=M12/TAPAREA;
M108=M13/TAPAREA; M109=M14/TAPAREA;


DISPLAY  M101, M102, M106, M10, M11,M12,M13,M14, M103, M104, M105,M106, M107
M108, M109;


H1(W)=SUM(S1, X112.L(S1,W)*TRCOST(S1,W));H2(W)=SUM(S3, X132.L(S3,W)*TRCOSTL(S3,W));
H3(F)=SUM(W,X212.L(W,F)*TTRUCOST(W,F)); H4(F)=SUM(W,X232.L(W,F)*TTRUCOST(W,F));
H5(F)=SUM(P1,DAACOST23 (P1,F)*X312.L(P1,F)); H6(F)=SUM(P2,LITACOST2 (P2,F)*X322.L(P2,F));
H7(W)= X412.L(W)*FWCOST1(W); H8(W)=X422.L(W)*FWCOST2(W);
H9(P1)=DAFICOST23(P1)*X512.L(P1);
H10(P2)=LIFICOST2(P2)*X522.L(P2); H11(W)=H1(W)+H2(W); H12(F)=H3(F)+H4(F);
H13=SUM(W,H11(W))+SUM(F,H12(F));H14=SUM(F, H5(F))+SUM(F,H6(F));
H15=SUM(W,H7(W))+SUM(W,H8(W)); H16=SUM(P1,H9(P1))+ SUM(P2,H10(P2));
H17=H13+H14+H15+H16; H101=SUM(W,H11(W)); H102= SUM(F,H12(F));H103=H101/TAPAREA;
H104=H102/TAPAREA; H105=H13/TAPAREA; H106=H14/TAPAREA; H107=H15/TAPAREA;
H108=H16/TAPAREA;
H109=H17/TAPAREA;

DISPLAY H101, H102, H13, H14,H15,H16,H17, H103, H104, H105,H106, H107, H108, H109 ;
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*****************************************************************************************
**This section analyses how changes in machinery working days affects the optimal number*
**  of equipment and operating costs                                                    *
*****************************************************************************************

*CASE1: INCREASE IN FALL AND SPRING WORKING DAYS

SCALAR IT1;
FOR (IT1 = 1 TO 23, DAYSFALL=DAYSFALL+(0.0132*DAYSFALL);DAYSSPR=DAYSSPR+(0.0132*DAYSSPR);

LITMCAP2(P2)=SUM(F,LIQCAP2(P2,F))*(DAYSSPR/14);
LITMCAP3(P2)=SUM(F,LIQCAP3(P2,F))*(DAYSSPR/14);
LITMCAP4(P2)=SUM(F,LIQCAP4(P2,F))*(DAYSSPR/14);
DAURTCAP1(P1)=SUM(F, DAPURCAP1(P1,F))*(DAYSFALL/14);
DATCAP23(P1)= SUM(F, DAPCAP23(P1,F))*(DAYSFALL/14);
DAURTCAP4(P1)=SUM(F, DAPURCAP4(P1,F))*(DAYSFALL/14);
ANTMCAP3(P3)=SUM(F,ANHYDCAP3 (P3,F))*(DAYSFALL/14);

SOLVE SYSTEM1 USING MIP MINIMIZING Z1;
SOLVE SYSTEM2 USING MIP MINIMIZING Z2;
SOLVE SYSTEM3 USING MIP MINIMIZING Z3;
SOLVE SYSTEM4 USING MIP MINIMIZING Z4;

DISPLAY  DAYSFALL,DAYSSPR, Z1.L,Z2.L,Z3.L,Z4.L;

R1(W)=SUM(S1, X113.L(S1,W)*TRCOST(S1,W)); R2(W)=SUM(S3, X133.L(S3,W)*TRCOSTL(S3,W));
R3(W)=SUM(S4, X143.L(S4,W)*TRANHY(S4,W)); R4(F)=SUM(W, X213.L(W,F)*TTRUCOST(W,F));
R5(F)=SUM(W, X243.L(W,F)*TTRUCOST(W,F));R6(F)=SUM(W, X233.L(W,F)*TTRUCOST(W,F));
R7(F)=SUM(P1, X313.L(P1,F)*DAACOST23(P1,F)); R8(F)=SUM(P2, X323.L(P2,F)*LITACOST3(P2,F));
R9(F)=SUM(P3, X333.L(P3,F)*AHTACOS3(P3,F)); R10(W)=X413.L(W)*FWCOST1(W);
R11(W)=X423.L(W)*FWCOST2(W); R12(W)=X433.L(W)*FWCOST3(W);
R13(P1)=DAFICOST23(P1)*X513.L(P1); R14(P2)=LIFICOST3(P2)*X523.L(P2);
R15(P3)=ANSFCOST3(P3)*X533.L(P3); R16(W)=R1(W)+R2(W)+R3(W); R17(F)=R4(F)+R5(F)+R6(F);
R18=SUM(W, R16(W))+SUM(F,R17(F)); R19=SUM(F,R7(F))+SUM(F,R8(F))+SUM(F,R9(F));
R20=SUM(W, R10(W))+SUM(W,R11(W))+SUM(W,R12(W));
R21=SUM(P1, R13(P1))+SUM(P2, R14(P2))+SUM(P3,R15(P3));
R22=R18+R19+R20+R21;
R100=SUM(F, R9(F));
R101=SUM(W,R16(W))/TAPAREA; R102=SUM(F,R17(F))/TAPAREA; R103=R18/TAPAREA;
R104=R19/TAPAREA;
R105=R20/TAPAREA; R106=R21/TAPAREA; R107=R22/TAPAREA;

DISPLAY R16, R17, R18,R19,R20,R21,R22, R100, R101, R102, R103, R104
R105, R106, R107;

JJ1(W)=SUM(S1, X114.L(S1,W)*TRCOST(S1,W)); J2(W)=SUM(S2,X124.L(S2,W)*TRCOSTU(S2,W));
J3(W)=SUM(S3, X134.L(S3,W)*TRCOSTL(S3,W)); J4(F)= SUM(W,X214.L(W,F)*TTRUCOST(W,F));
J5(F)=SUM(W,X224.L(W,F)*TTRUCOST(W,F)); J6(F)=SUM(W,X234.L(W,F)*TTRUCOST(W,F));
J7(F)=SUM(P1,MITACOST4 (P1,F)*X314.L(P1,F)); J8(F)=SUM(P2,LITACOST4(P2,F)*X324.L(P2,F));
J9(W)=X414.L(W)*FWCOST1(W); J10(W)=X424.L(W)*FWCOST2(W);
J11(P1)=MIFICOST4(P1)*X514.L(P1);
J12(P2)=LIFICOST4(P2)*X524.L(P2); J13(W)=J1(W)+J2(W)+J3(W); J14(F)=J4(F)+J5(F)+J6(F);
J15=SUM(W,J13(W))+SUM(F,J14(F));
J16=SUM(W,J9(W))+SUM(W,J10(W));
J17=SUM(F,J7(F))+SUM(F,J8(F));
J18=SUM(P1,J11(P1))+SUM(P2,J12(P2));
J19=J15+J16+J17+J18;
J101=SUM(W,J13(W))/TAPAREA; J102=SUM(F,J14(F))/TAPAREA; J103=J15/TAPAREA;
J104=J16/TAPAREA;J105= J17/TAPAREA; J106=J18/TAPAREA;
J107=J19/TAPAREA;

DISPLAY  J13, J14, J15,J16,J17,J18,J19, J101, J102, J103, J104
J105, J106, J107;

M1(W)=SUM(S1, X111.L(S1,W)*TRCOST(S1,W)); M2(W)=SUM(S2,X121.L(S2,W)*TRCOSTU(S2,W));
M3(F)=SUM(W,X211.L(W,F)*TTRUCOST(W,F));M4(F)=SUM(W,X221.L(W,F)*TTRUCOST(W,F));
M5(F)=SUM(P1,MITACOST1 (P1,F)*X311.L(P1,F));M6(W)=X411.L(W)*FWCOST1(W);
M7(P1)=MIFICOST1(P1)*X511.L(P1); M8(W)=M1(W)+M2(W);M9(F)=M3(F)+M4(F);
M10=SUM(W, M8(W))+SUM(F,M9(F));
M11=SUM(P1,M7(P1));M12=SUM(W,M6(W)); M13=SUM(F,M5(F));
M14=M10+M11+M12+M13;
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*****************************************************************************************
**This section analyses how changes in machinery working days affects the optimal number*
**  of equipment and operating costs                                                    *
*****************************************************************************************

*CASE1: INCREASE IN FALL AND SPRING WORKING DAYS

SCALAR IT1;
FOR (IT1 = 1 TO 23, DAYSFALL=DAYSFALL+(0.0132*DAYSFALL);DAYSSPR=DAYSSPR+(0.0132*DAYSSPR);

LITMCAP2(P2)=SUM(F,LIQCAP2(P2,F))*(DAYSSPR/14);
LITMCAP3(P2)=SUM(F,LIQCAP3(P2,F))*(DAYSSPR/14);
LITMCAP4(P2)=SUM(F,LIQCAP4(P2,F))*(DAYSSPR/14);
DAURTCAP1(P1)=SUM(F, DAPURCAP1(P1,F))*(DAYSFALL/14);
DATCAP23(P1)= SUM(F, DAPCAP23(P1,F))*(DAYSFALL/14);
DAURTCAP4(P1)=SUM(F, DAPURCAP4(P1,F))*(DAYSFALL/14);
ANTMCAP3(P3)=SUM(F,ANHYDCAP3 (P3,F))*(DAYSFALL/14);

SOLVE SYSTEM1 USING MIP MINIMIZING Z1;
SOLVE SYSTEM2 USING MIP MINIMIZING Z2;
SOLVE SYSTEM3 USING MIP MINIMIZING Z3;
SOLVE SYSTEM4 USING MIP MINIMIZING Z4;

DISPLAY  DAYSFALL,DAYSSPR, Z1.L,Z2.L,Z3.L,Z4.L;

R1(W)=SUM(S1, X113.L(S1,W)*TRCOST(S1,W)); R2(W)=SUM(S3, X133.L(S3,W)*TRCOSTL(S3,W));
R3(W)=SUM(S4, X143.L(S4,W)*TRANHY(S4,W)); R4(F)=SUM(W, X213.L(W,F)*TTRUCOST(W,F));
R5(F)=SUM(W, X243.L(W,F)*TTRUCOST(W,F));R6(F)=SUM(W, X233.L(W,F)*TTRUCOST(W,F));
R7(F)=SUM(P1, X313.L(P1,F)*DAACOST23(P1,F)); R8(F)=SUM(P2, X323.L(P2,F)*LITACOST3(P2,F));
R9(F)=SUM(P3, X333.L(P3,F)*AHTACOS3(P3,F)); R10(W)=X413.L(W)*FWCOST1(W);
R11(W)=X423.L(W)*FWCOST2(W); R12(W)=X433.L(W)*FWCOST3(W);
R13(P1)=DAFICOST23(P1)*X513.L(P1); R14(P2)=LIFICOST3(P2)*X523.L(P2);
R15(P3)=ANSFCOST3(P3)*X533.L(P3); R16(W)=R1(W)+R2(W)+R3(W); R17(F)=R4(F)+R5(F)+R6(F);
R18=SUM(W, R16(W))+SUM(F,R17(F)); R19=SUM(F,R7(F))+SUM(F,R8(F))+SUM(F,R9(F));
R20=SUM(W, R10(W))+SUM(W,R11(W))+SUM(W,R12(W));
R21=SUM(P1, R13(P1))+SUM(P2, R14(P2))+SUM(P3,R15(P3));
R22=R18+R19+R20+R21;
R100=SUM(F, R9(F));
R101=SUM(W,R16(W))/TAPAREA; R102=SUM(F,R17(F))/TAPAREA; R103=R18/TAPAREA;
R104=R19/TAPAREA;
R105=R20/TAPAREA; R106=R21/TAPAREA; R107=R22/TAPAREA;

DISPLAY R16, R17, R18,R19,R20,R21,R22, R100, R101, R102, R103, R104
R105, R106, R107;

JJ1(W)=SUM(S1, X114.L(S1,W)*TRCOST(S1,W)); J2(W)=SUM(S2,X124.L(S2,W)*TRCOSTU(S2,W));
J3(W)=SUM(S3, X134.L(S3,W)*TRCOSTL(S3,W)); J4(F)= SUM(W,X214.L(W,F)*TTRUCOST(W,F));
J5(F)=SUM(W,X224.L(W,F)*TTRUCOST(W,F)); J6(F)=SUM(W,X234.L(W,F)*TTRUCOST(W,F));
J7(F)=SUM(P1,MITACOST4 (P1,F)*X314.L(P1,F)); J8(F)=SUM(P2,LITACOST4(P2,F)*X324.L(P2,F));
J9(W)=X414.L(W)*FWCOST1(W); J10(W)=X424.L(W)*FWCOST2(W);
J11(P1)=MIFICOST4(P1)*X514.L(P1);
J12(P2)=LIFICOST4(P2)*X524.L(P2); J13(W)=J1(W)+J2(W)+J3(W); J14(F)=J4(F)+J5(F)+J6(F);
J15=SUM(W,J13(W))+SUM(F,J14(F));
J16=SUM(W,J9(W))+SUM(W,J10(W));
J17=SUM(F,J7(F))+SUM(F,J8(F));
J18=SUM(P1,J11(P1))+SUM(P2,J12(P2));
J19=J15+J16+J17+J18;
J101=SUM(W,J13(W))/TAPAREA; J102=SUM(F,J14(F))/TAPAREA; J103=J15/TAPAREA;
J104=J16/TAPAREA;J105= J17/TAPAREA; J106=J18/TAPAREA;
J107=J19/TAPAREA;

DISPLAY  J13, J14, J15,J16,J17,J18,J19, J101, J102, J103, J104
J105, J106, J107;

M1(W)=SUM(S1, X111.L(S1,W)*TRCOST(S1,W)); M2(W)=SUM(S2,X121.L(S2,W)*TRCOSTU(S2,W));
M3(F)=SUM(W,X211.L(W,F)*TTRUCOST(W,F));M4(F)=SUM(W,X221.L(W,F)*TTRUCOST(W,F));
M5(F)=SUM(P1,MITACOST1 (P1,F)*X311.L(P1,F));M6(W)=X411.L(W)*FWCOST1(W);
M7(P1)=MIFICOST1(P1)*X511.L(P1); M8(W)=M1(W)+M2(W);M9(F)=M3(F)+M4(F);
M10=SUM(W, M8(W))+SUM(F,M9(F));
M11=SUM(P1,M7(P1));M12=SUM(W,M6(W)); M13=SUM(F,M5(F));
M14=M10+M11+M12+M13;
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M101=SUM(W, M8(W));M102=SUM(F,M9(F));
M103=SUM(W, M8(W))/TAPAREA; M104=SUM(F,M9(F))/TAPAREA;
M105=M10/TAPAREA; M106=M11/TAPAREA; M107=M12/TAPAREA;
M108=M13/TAPAREA; M109=M14/TAPAREA;


DISPLAY  M101, M102, M106, M10, M11,M12,M13,M14, M103, M104, M105,M106, M107
M108, M109;


H1(W)=SUM(S1, X112.L(S1,W)*TRCOST(S1,W));H2(W)=SUM(S3, X132.L(S3,W)*TRCOSTL(S3,W));
H3(F)=SUM(W,X212.L(W,F)*TTRUCOST(W,F)); H4(F)=SUM(W,X232.L(W,F)*TTRUCOST(W,F));
H5(F)=SUM(P1,DAACOST23 (P1,F)*X312.L(P1,F)); H6(F)=SUM(P2,LITACOST2 (P2,F)*X322.L(P2,F));
H7(W)= X412.L(W)*FWCOST1(W); H8(W)=X422.L(W)*FWCOST2(W);
H9(P1)=DAFICOST23(P1)*X512.L(P1);
H10(P2)=LIFICOST2(P2)*X522.L(P2); H11(W)=H1(W)+H2(W); H12(F)=H3(F)+H4(F);
H13=SUM(W,H11(W))+SUM(F,H12(F));H14=SUM(F, H5(F))+SUM(F,H6(F));
H15=SUM(W,H7(W))+SUM(W,H8(W)); H16=SUM(P1,H9(P1))+ SUM(P2,H10(P2));
H17=H13+H14+H15+H16; H101=SUM(W,H11(W)); H102= SUM(F,H12(F));H103=H101/TAPAREA;
H104=H102/TAPAREA; H105=H13/TAPAREA; H106=H14/TAPAREA; H107=H15/TAPAREA;
H108=H16/TAPAREA;
H109=H17/TAPAREA;

DISPLAY H101, H102, H13, H14,H15,H16,H17, H103, H104, H105,H106, H107, H108, H109) ;

*CASE2: DECREASE IN FALL AND SPRING WORKING DAYS

SCALAR
DAYFALL WORKING DAYS IN FALL
DAYSPR WORKING DAYS IN SPRING;
DAYFALL=45;
DAYSPR=21

SCALAR IT1;
FOR (IT1 = 1 TO 29, DAYFALL=DAYFALL-(0.0142*DAYFALL);DAYSPR=DAYSPR-(0.0142*DAYSPR);

LITMCAP2(P2)=SUM(F,LIQCAP2(P2,F))*(DAYSPR/14);
LITMCAP3(P2)=SUM(F,LIQCAP3(P2,F))*(DAYSPR/14);
LITMCAP4(P2)=SUM(F,LIQCAP4(P2,F))*(DAYSPR/14);
DAURTCAP1(P1)=SUM(F, DAPURCAP1(P1,F))*(DAYFALL/14);
DATCAP23(P1)= SUM(F, DAPCAP23(P1,F))*(DAYFALL/14);
DAURTCAP4(P1)=SUM(F, DAPURCAP4(P1,F))*(DAYFALL/14);
ANTMCAP3(P3)=SUM(F,ANHYDCAP3 (P3,F))*(DAYFALL/14);

SOLVE SYSTEM1 USING MIP MINIMIZING Z1;
SOLVE SYSTEM2 USING MIP MINIMIZING Z2;
SOLVE SYSTEM3 USING MIP MINIMIZING Z3;
SOLVE SYSTEM4 USING MIP MINIMIZING Z4;

DISPLAY  DAYFALL,DAYSPR, Z1.L,Z2.L,Z3.L,Z4.L;

R1(W)=SUM(S1, X113.L(S1,W)*TRCOST(S1,W)); R2(W)=SUM(S3, X133.L(S3,W)*TRCOSTL(S3,W));
R3(W)=SUM(S4, X143.L(S4,W)*TRANHY(S4,W)); R4(F)=SUM(W, X213.L(W,F)*TTRUCOST(W,F));
R5(F)=SUM(W, X243.L(W,F)*TTRUCOST(W,F));R6(F)=SUM(W, X233.L(W,F)*TTRUCOST(W,F));
R7(F)=SUM(P1, X313.L(P1,F)*DAACOST23(P1,F)); R8(F)=SUM(P2, X323.L(P2,F)*LITACOST3(P2,F));
R9(F)=SUM(P3, X333.L(P3,F)*AHTACOS3(P3,F)); R10(W)=X413.L(W)*FWCOST1(W);
R11(W)=X423.L(W)*FWCOST2(W); R12(W)=X433.L(W)*FWCOST3(W);
R13(P1)=DAFICOST23(P1)*X513.L(P1); R14(P2)=LIFICOST3(P2)*X523.L(P2);
R15(P3)=ANSFCOST3(P3)*X533.L(P3); R16(W)=R1(W)+R2(W)+R3(W); R17(F)=R4(F)+R5(F)+R6(F);
R18=SUM(W, R16(W))+SUM(F,R17(F)); R19=SUM(F,R7(F))+SUM(F,R8(F))+SUM(F,R9(F));
R20=SUM(W, R10(W))+SUM(W,R11(W))+SUM(W,R12(W));
R21=SUM(P1, R13(P1))+SUM(P2, R14(P2))+SUM(P3,R15(P3));
R22=R18+R19+R20+R21;
R100=SUM(F, R9(F));
R101=SUM(W,R16(W))/TAPAREA; R102=SUM(F,R17(F))/TAPAREA; R103=R18/TAPAREA;
R104=R19/TAPAREA;
R105=R20/TAPAREA; R106=R21/TAPAREA; R107=R22/TAPAREA;

DISPLAY R16, R17, R18,R19,R20,R21,R22, R100, R101, R102, R103, R104
R105, R106, R107;
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JJ1(W)=SUM(S1, X114.L(S1,W)*TRCOST(S1,W)); J2(W)=SUM(S2,X124.L(S2,W)*TRCOSTU(S2,W));
J3(W)=SUM(S3, X134.L(S3,W)*TRCOSTL(S3,W)); J4(F)= SUM(W,X214.L(W,F)*TTRUCOST(W,F));
J5(F)=SUM(W,X224.L(W,F)*TTRUCOST(W,F)); J6(F)=SUM(W,X234.L(W,F)*TTRUCOST(W,F));
J7(F)=SUM(P1,MITACOST4 (P1,F)*X314.L(P1,F)); J8(F)=SUM(P2,LITACOST4(P2,F)*X324.L(P2,F));
J9(W)=X414.L(W)*FWCOST1(W); J10(W)=X424.L(W)*FWCOST2(W);
J11(P1)=MIFICOST4(P1)*X514.L(P1);
J12(P2)=LIFICOST4(P2)*X524.L(P2); J13(W)=J1(W)+J2(W)+J3(W); J14(F)=J4(F)+J5(F)+J6(F);
J15=SUM(W,J13(W))+SUM(F,J14(F));
J16=SUM(W,J9(W))+SUM(W,J10(W));
J17=SUM(F,J7(F))+SUM(F,J8(F));
J18=SUM(P1,J11(P1))+SUM(P2,J12(P2));
J19=J15+J16+J17+J18;
J101=SUM(W,J13(W))/TAPAREA; J102=SUM(F,J14(F))/TAPAREA; J103=J15/TAPAREA;
J104=J16/TAPAREA;J105= J17/TAPAREA; J106=J18/TAPAREA;
J107=J19/TAPAREA;

DISPLAY  J13, J14, J15,J16,J17,J18,J19, J101, J102, J103, J104
J105, J106, J107;

M1(W)=SUM(S1, X111.L(S1,W)*TRCOST(S1,W)); M2(W)=SUM(S2,X121.L(S2,W)*TRCOSTU(S2,W));
M3(F)=SUM(W,X211.L(W,F)*TTRUCOST(W,F));M4(F)=SUM(W,X221.L(W,F)*TTRUCOST(W,F));
M5(F)=SUM(P1,MITACOST1 (P1,F)*X311.L(P1,F));M6(W)=X411.L(W)*FWCOST1(W);
M7(P1)=MIFICOST1(P1)*X511.L(P1); M8(W)=M1(W)+M2(W);M9(F)=M3(F)+M4(F);
M10=SUM(W, M8(W))+SUM(F,M9(F));
M11=SUM(P1,M7(P1));M12=SUM(W,M6(W)); M13=SUM(F,M5(F));
M14=M10+M11+M12+M13;
M101=SUM(W, M8(W));M102=SUM(F,M9(F));
M103=SUM(W, M8(W))/TAPAREA; M104=SUM(F,M9(F))/TAPAREA;
M105=M10/TAPAREA; M106=M11/TAPAREA; M107=M12/TAPAREA;
M108=M13/TAPAREA; M109=M14/TAPAREA;

DISPLAY M101, M102, M106, M10, M11,M12, M13, M14, M103, M104, M105,M106, M107
M108, M109;

H1(W)=SUM(S1, X112.L(S1,W)*TRCOST(S1,W));H2(W)=SUM(S3, X132.L(S3,W)*TRCOSTL(S3,W));
H3(F)=SUM(W,X212.L(W,F)*TTRUCOST(W,F)); H4(F)=SUM(W,X232.L(W,F)*TTRUCOST(W,F));
H5(F)=SUM(P1,DAACOST23 (P1,F)*X312.L(P1,F)); H6(F)=SUM(P2,LITACOST2 (P2,F)*X322.L(P2,F));
H7(W)= X412.L(W)*FWCOST1(W); H8(W)=X422.L(W)*FWCOST2(W);
H9(P1)=DAFICOST23(P1)*X512.L(P1);
H10(P2)=LIFICOST2(P2)*X522.L(P2); H11(W)=H1(W)+H2(W); H12(F)=H3(F)+H4(F);
H13=SUM(W,H11(W))+SUM(F,H12(F));H14=SUM(F, H5(F))+SUM(F,H6(F));
H15=SUM(W,H7(W))+SUM(W,H8(W)); H16=SUM(P1,H9(P1))+ SUM(P2,H10(P2));
H17=H13+H14+H15+H16; H101=SUM(W,H11(W)); H102= SUM(F,H12(F));H103=H101/TAPAREA;
H104=H102/TAPAREA; H105=H13/TAPAREA; H106=H14/TAPAREA; H107=H15/TAPAREA;
H108=H16/TAPAREA;
H109=H17/TAPAREA;

DISPLAY H101, H102, H13, H14,H15, H16,H17, H103, H104, H105,H106, H107, H108, H109) ;

****************************************************************************
* This section analyses how "big" and "cheap" the central warehouses      **
* should be to make a complete centralization feasible                    **
****************************************************************************

*************************
**CASE1: Baseline model**
*************************
Parameter
CAPWD2 (W) Ideal dry storage capacity for a central warehouse in tons
/CKing      20000
 King        4000
 Okar        4000
 Yuko        4000
 Omeg        4000
 Pied        4000
 Wato        4000
 Henn        4000/
```

```
CAPWL2  (W) Ideal UAN storage capacity for a central warehouse in tons
/CKing        10000
 King          4000
 Okar          4000
 Yuko          4000
 Omeg          4000
 Pied          4000
 Wato          4000
 Henn          4000/


COST11  (W) Fixed cost for ownership of dry storage per year in dollars
/CKing        12249.77
 King         7000
 Okar         7000
 Yuko         7000
 Omeg         7000
 Pied         7000
 Wato         7000
 Henn         7000/


COST22  (W) Fixed cost for ownership of UAN storage per year in dollars
/CKing     6999.87
 King        8000
 Okar        8000
 Yuko        8000
 Omeg        8000
 Pied        8000
 Wato        8000
 Henn        8000/

OPCOST11(W) Opportunity cost of funds used to acquire dry storage in dollars per year
OPCOST22(W) Opportunity cost of funds used to acquire UAN storage in dollars per year
PVINTX11  (W) Property value insurance and tax for dry storage
PVINTX22  (W) Property value insurance and tax for UAN storage
MAINCOST11  (W) Maintenance cost for dry storage
MAINCOST22  (W) Maintenance cost for UAN storage
FWCOST11  (W) Total cost for dry warehousing per year in dollars
FWCOST22  (W) Total cost for UAN warehousing per year in dollars
DRYPTC11  (W) Per ton cost for dry storage in dollars
LIQPTC22  (W) Per ton cost for liquid storage in dollars;
OPCOST11(W)=(0.5*COST11(W)*0.08);
OPCOST22(W)=(0.5*COST22(W)*0.08);
PVINTX11  (W)=COST11(W)*0.025*40 ;
PVINTX22  (W)=COST22(W)*0.025*40;
MAINCOST11  (W)=COST11(W)*0.03*40;
MAINCOST22  (W)=COST22(W)*0.03*40;
FWCOST11  (W)= COST11(W)+OPCOST11(W)+PVINTX11(W)+MAINCOST11(W);
FWCOST22  (W)= COST22(W)+OPCOST22(W)+PVINTX22(W)+MAINCOST22(W);

EQUATIONS

COST_11  objective function_system1

CAPACD33(W)  Observe storage capacity for dry fertilizers (DAP only)_system1
CAPACL33(W)  Observe warehouse storage capacity for UAN fertilizers_system1;

CAPACD33(W)..SUM(S1,X113(S1,W))=L=X413(W)*CAPWD2(W);
CAPACL33(W)..SUM(S3,X133(S3,W))=L=X423(W)*CAPWL2(W);
COST_11..Z1=E=SUM((S1,W), X113(S1,W)*TRCOST(S1,W))+ SUM((S3,W), X133(S3,W)*TRCOSTL(S3,W))
             +SUM((S4,W), X143(S4,W)*TRANHY  (S4,W))+SUM((W,F),X213(W,F)*TTRUCOST(W,F))
             +SUM((W,F),X243(W,F)*TTRUCOST(W,F))+SUM((W,F),X233(W,F)*TTRUCOST(W,F))
             + SUM((P1,F),DAACOST23(P1,F)*X313(P1,F))+ SUM((P3,F),AHTACOS3  (P3,F)
             *X333
(P3,F))+SUM((P2,F),LITACOST3(P2,F)*X323(P2,F))+SUM(W,X413(W)*FWCOST11(W))

+SUM(W,X423(W)*FWCOST22(W))+SUM(W,X433(W)*FWCOST3(W))+SUM(P1,DAFICOST23(P1)*X513(P1))
             +SUM(P3, ANSFCOST3(P3)*X533(P3))+ SUM(P2,LIFICOST3(P2)*X523(P2));
```

```
MODEL SYSTEM11/COST_11,DAPSUP3,ANYSUP3,CAPACD33,CAPACAN3,DAPDEM3,ANYDDEM3
                DAPBAL3,CAPACL33, ANHYBAL3,APPLYD3, LIQSUP3, LIQDEM3, LIQBAL3
                APPLYL3,APLOCL3, APPLYAN3, APLOCD3, APLOCAN3/;
SCALAR IT;
for (IT=1 to 150, FWCOST11("CKING")=FWCOST11("CKING")-2000;
FWCOST22("CKING")=FWCOST22("CKING")-2000;
DRYPTC11 (W)=FWCOST11 (W)/CAPWD2 (W);
LIQPTC22 (W)=FWCOST22 (W)/CAPWL2 (W);

SOLVE SYSTEM11 USING MIP MINIMIZING Z1;

DISPLAY FWCOST11,FWCOST22,DRYPTC11,LIQPTC22, Z1.L;

R1(W)=SUM(S1, X113.L(S1,W)*TRCOST(S1,W)); R2(W)=SUM(S3, X133.L(S3,W)*TRCOSTL(S3,W));
R3(W)=SUM(S4, X143.L(S4,W)*TRANHY(S4,W)); R4(F)=SUM(W, X213.L(W,F)*TTRUCOST(W,F));
R5(F)=SUM(W, X243.L(W,F)*TTRUCOST(W,F));R6(F)=SUM(W, X233.L(W,F)*TTRUCOST(W,F));
R7(F)=SUM(P1, X313.L(P1,F)*DAACOST23(P1,F)); R8(F)=SUM(P2, X323.L(P2,F)*LITACOST3(P2,F));
R9(F)=SUM(P3, X333.L(P3,F)*AHTACOS3(P3,F)); R10(W)=X413.L(W)*FWCOST1(W);
R11(W)=X423.L(W)*FWCOST2(W); R12(W)=X433.L(W)*FWCOST3(W);
R13(P1)=DAFICOST23(P1)*X513.L(P1); R14(P2)=LIFICOST3(P2)*X523.L(P2);
R15(P3)=ANSFCOST3(P3)*X533.L(P3); R16(W)=R1(W)+R2(W)+R3(W); R17(F)=R4(F)+R5(F)+R6(F);
R18=SUM(W, R16(W))+SUM(F,R17(F)); R19=SUM(F,R7(F))+SUM(F,R8(F))+SUM(F,R9(F));
R20=SUM(W, R10(W))+SUM(W,R11(W))+SUM(W,R12(W));
R21=SUM(P1, R13(P1))+SUM(P2, R14(P2))+SUM(P3,R15(P3));
R22=R18+R19+R20+R21;
R100=SUM(F, R9(F));
R101=SUM(W, R16(W))/TAPAREA; R102=SUM(F,R17(F))/TAPAREA; R103=R18/TAPAREA;
R104=R19/TAPAREA;
R105=R20/TAPAREA; R106=R21/TAPAREA; R107=R22/TAPAREA;

DISPLAY R16, R17, R18,R19,R20,R21,R22, R100, R101, R102, R103, R104
R105, R106, R107);

*********************************************************
**CASE2: DAP+UREA+UAN (MODEL 2)                        **
*********************************************************

Parameter
CAPWD4 (W) Ideal dry storage capacity for a central warehouse in tons
/CKing       20000
 King         4000
 Okar         4000
 Yuko         4000
 Omeg         4000
 Pied         4000
 Wato         4000
 Henn         4000/

CAPWL4 (W) Ideal UAN storage capacity for a central warehouse in tons
/CKing      10000
 King        4000
 Okar        4000
 Yuko        4000
 Omeg        4000
 Pied        4000
 Wato        4000
 Henn        4000/


COSTDW (W) Fixed cost for ownership of dry storage per year in dollars
/CKing      12249.77
 King       7000
 Okar       7000
 Yuko       7000
 Omeg       7000
 Pied       7000
 Wato       7000
 Henn       7000/
```

```
COSTLW (W) Fixed cost for ownership of UAN storage per year in dollars
/CKing    6999.87
 King       8000
 Okar       8000
 Yuko       8000
 Omeg       8000
 Pied       8000
 Wato       8000
 Henn       8000/

OPCOSTD(W) Opportunity cost of funds used to acquire dry storage in dollars per year
OPCOSTL(W) Opportunity cost of funds used to acquire UAN storage in dollars per year
PVINTXD (W) Property value insurance and tax for dry storage
PVINTXL (W) Property value insurance and tax for UAN storage
MAINCOSTD (W) Maintenance cost for dry storage
MAINCOSTL (W) Maintenance cost for UAN storage
FWCOSTD (W) Total cost for dry warehousing per year in dollars
FWCOSTL (W) Total cost for UAN warehousing per year in dollars
DRYPTCOST (W) Per ton cost for dry warehousing in dollars
LIQPTCOST (W) Per ton cost for liquid warehousing in dollars;
OPCOSTD(W)=(0.5*COSTDW(W)*0.08);
OPCOSTL(W)=(0.5*COSTLW(W)*0.08);
PVINTXD (W)=COSTDW(W)*0.025*40 ;
PVINTXL (W)=COSTLW(W)*0.025*40;
MAINCOSTD (W)=COSTDW(W)*0.03*40;
MAINCOSTL (W)=COSTLW(W)*0.03*40;
FWCOSTD (W)= COSTDW(W)+OPCOSTD(W)+PVINTXD(W)+MAINCOSTD(W);
FWCOSTL (W)= COSTLW(W)+OPCOSTL(W)+PVINTXL(W)+MAINCOSTL(W);


EQUATIONS
COST_22  objective function_system2
CAPACD44(W)  Observe storage capacity for dry fertilizers (DAP and UREA)_system2
CAPACL44(W)  Observe warehouse storage capacity for UAN fertilizers_system2;
CAPACD44(W)..SUM(S1,X114(S1,W))+SUM(S2,X124(S2,W))=L=X414(W)*CAPWD4(W);
CAPACL44(W)..SUM(S3,X134(S3,W))=L=X424(W)*CAPWL4(W);

COST_22..Z2=E=SUM((S1,W), X114(S1,W)*TRCOST(S1,W))+SUM((S2,W), X124(S2,W)*TRCOSTU(S2,W))
              +SUM((S3,W), X134(S3,W)*TRCOSTL(S3,W))+SUM((W,F),X214(W,F)*TTRUCOST(W,F))
              +SUM((W,F),X224(W,F)*TTRUCOST(W,F))+SUM((W,F),X234(W,F)*TTRUCOST(W,F))
              +SUM((P1,F),MITACOST4
(P1,F)*X314(P1,F))+SUM((P2,F),LITACOST4(P2,F)*X324(P2,F))

+SUM(W,X414(W)*FWCOSTD(W))+SUM(W,X424(W)*FWCOSTL(W))+SUM(P1,MIFICOST4(P1)*X514(P1))
              +SUM(P2,LIFICOST4(P2)*X524(P2));

MODEL SYSTEM22/COST_22,DAPSUP4,UREASUP4,LIQSUP4,CAPACD44,CAPACL44,DAPDEM4,UREADEM4
               DAPBAL4, LIQDEM4, UREABAL4, LIQBAL4, APLOCD4, APLOCL4, MIXRATI4
               APPLYL4/ ;

SCALAR IT;
for (IT=1 to 150 , FWCOSTD("CKING")=FWCOSTD("CKING")-2000;
FWCOSTL("CKING")=FWCOSTL("CKING")-2000;
DRYPTCOST (W)=FWCOSTD (W)/CAPWD4 (W);
LIQPTCOST (W)=FWCOSTL (W)/CAPWL4 (W);

SOLVE SYSTEM22 USING MIP MINIMIZING Z2;

DISPLAY FWCOSTD, FWCOSTL, DRYPTCOST, LIQPTCOST, Z2.L;

J1(W)=SUM(S1, X114.L(S1,W)*TRCOST(S1,W)); J2(W)=SUM(S2,X124.L(S2,W)*TRCOSTU(S2,W));
J3(W)=SUM(S3, X134.L(S3,W)*TRCOSTL(S3,W)); J4(F)= SUM(W,X214.L(W,F)*TTRUCOST(W,F));
J5(F)=SUM(W,X224.L(W,F)*TTRUCOST(W,F)); J6(F)=SUM(W,X234.L(W,F)*TTRUCOST(W,F));
J7(F)=SUM(P1,MITACOST4 (P1,F)*X314.L(P1,F)); J8(F)=SUM(P2,LITACOST4(P2,F)*X324.L(P2,F));
J9(W)=X414.L(W)*FWCOST1(W); J10(W)=X424.L(W)*FWCOST2(W);
J11(P1)=MIFICOST4(P1)*X514.L(P1);
J12(P2)=LIFICOST4(P2)*X524.L(P2); J13(W)=J1(W)+J2(W)+J3(W); J14(F)=J4(F)+J5(F)+J6(F);
J15=SUM(W,J13(W))+SUM(F,J14(F));
J16=SUM(W,J9(W))+SUM(W,J10(W));
J17=SUM(F,J7(F))+SUM(F,J8(F));
J18=SUM(P1,J11(P1))+SUM(P2,J12(P2));
```

```
J19=J15+J16+J17+J18;
J101=SUM(W,J13(W))/TAPAREA; J102=SUM(F,J14(F))/TAPAREA; J103=J15/TAPAREA;
J104=J16/TAPAREA; J105=J17/TAPAREA; J106=J18/TAPAREA;
J107=J19/TAPAREA;

DISPLAY  J13, J14, J15,J16,J17,J18,J19, J101, J102, J103, J104
J105, J106, J107);

*********************************************************************
* CASE 3: DAP AND UREA ONLY (MODEL 3)                              **
*********************************************************************


Parameter
CAPWD3 (W) Ideal dry storage capacity for a central warehouse in tons
/CKing        20000
 King          4000
 Okar          4000
 Yuko          4000
 Omeg          4000
 Pied          4000
 Wato          4000
 Henn          4000/

COSTDW3 (W) Fixed cost for ownership of dry storage per year in dollars
/CKing       12249.77
 King        7000
 Okar        7000
 Yuko        7000
 Omeg        7000
 Pied        7000
 Wato        7000
 Henn        7000/

OPCOSTD3(W) Opportunity cost of funds used to acquire dry storage in dollars per year
PVINTXD3 (W) Property value insurance and tax for dry storage
MAINCOSTD3 (W) Maintenance cost for dry storage
FWCOSTD3 (W) Total cost for dry warehousing per year in dollars
DRYCPT3 (W) Per ton storage cost for dry fertilizers;
OPCOSTD3(W)=(0.5*COSTDW3(W)*0.08);
PVINTXD3 (W)=COSTDW3(W)*0.025*40 ;
MAINCOSTD3 (W)=COSTDW3(W)*0.03*40;
FWCOSTD3 (W)= COSTDW3(W)+OPCOSTD3(W)+PVINTXD3(W)+MAINCOSTD3(W);

EQUATIONS

COST_33  objective function_system3
CAPACDS3(W)  Observe storage capacity for dry fertilizers (DAP and UREA)_system3 ;

COST_33..Z3=E= SUM((S1,W), X111(S1,W)*TRCOST(S1,W))+SUM((S2,W), X121(S2,W)
              *TRCOSTU(S2,W))+SUM((W,F),X211(W,F)*TTRUCOST(W,F))
              +SUM((W,F),X221(W,F)*TTRUCOST(W,F))+SUM((P1,F),MITACOST1 (P1,F)
              *X311(P1,F))+SUM(W,X411(W)*FWCOSTD3(W))+ SUM(P1,MIFICOST1(P1)*X511(P1));

CAPACDS3(W)..SUM(S1,X111(S1,W))+SUM(S2,X121(S2,W))=L=X411(W)*CAPWD3(W);

MODEL SYSTEM33 /COST_33,
DAPSUP1,UREASUP1,CAPACDS3,DAPDEM1,UREADEM1,DAPBAL1,UREABAL1,APLOCD1
               MIXRATI1/;

SCALAR IT;
for (IT=1 to 150, FWCOSTD3("CKING")=FWCOSTD3("CKING")-2000;
DRYCPT3 (W)= FWCOSTD3 (W)/CAPWD3 (W);


SOLVE SYSTEM33 USING MIP MINIMIZING Z3;

DISPLAY FWCOSTD3, DRYCPT3,Z3.L;

M1(W)=SUM(S1, X111.L(S1,W)*TRCOST(S1,W)); M2(W)=SUM(S2,X121.L(S2,W)*TRCOSTU(S2,W));
M3(F)=SUM(W,X211.L(W,F)*TTRUCOST(W,F));M4(F)=SUM(W,X221.L(W,F)*TTRUCOST(W,F));
M5(F)=SUM(P1,MITACOST1 (P1,F)*X311.L(P1,F));M6(W)=X411.L(W)*FWCOST1(W);
```

```
M7(P1)=MIFICOST1(P1)*X511.L(P1); M8(W)=M1(W)+M2(W);M9(F)=M3(F)+M4(F);
M10=SUM(W, M8(W))+SUM(F,M9(F));
M11=SUM(P1,M7(P1));M12=SUM(W,M6(W)); M13=SUM(F,M5(F));
M14=M10+M11+M12+M13;
M101=SUM(W, M8(W));M102=SUM(F,M9(F));
M103=SUM(W, M8(W))/TAPAREA; M104=SUM(F,M9(F))/TAPAREA;
M105=M10/TAPAREA; M106=M11/TAPAREA; M107=M12/TAPAREA;
M108=M13/TAPAREA; M109=M14/TAPAREA;


DISPLAY  M101, M102, M106, M10, M11,M12,M13,M14, M103, M104, M105,M106, M107
M108, M109);

***********************************************************************
**CASE4: DAP AND UAN (MODEL 4)                                       **
***********************************************************************

Parameter
CAPWDS4 (W) Ideal dry storage capacity for a central warehouse in tons
/CKing        20000
 King          4000
 Okar          4000
 Yuko          4000
 Omeg          4000
 Pied          4000
 Wato          4000
 Henn          4000/

CAPWLS4 (W) Ideal UAN storage capacity for a central warehouse in tons
/CKing        10000
 King         4000
 Okar         4000
 Yuko         4000
 Omeg         4000
 Pied         4000
 Wato         4000
 Henn         4000/

COSTD4 (W) Fixed cost for ownership of dry storage per year in dollars
/CKing       12249.77
 King        7000
 Okar        7000
 Yuko        7000
 Omeg        7000
 Pied        7000
 Wato        7000
 Henn        7000/

COSTL4 (W) Fixed cost for ownership of UAN storage per year in dollars
/CKing     6999.87
 King        8000
 Okar        8000
 Yuko        8000
 Omeg        8000
 Pied        8000
 Wato        8000
 Henn        8000/

OPCOSTD4(W) Opportunity cost of funds used to acquire dry storage in dollars per year
OPCOSTL4(W) Opportunity cost of funds used to acquire UAN storage in dollars per year
PVINTXD4 (W) Property value insurance and tax for dry storage
PVINTXL4 (W) Property value insurance and tax for UAN storage
MAINCOSTD4 (W) Maintenance cost for dry storage
MAINCOSTL4 (W) Maintenance cost for UAN storage
FWCOSTD4 (W) Total cost for dry warehousing per year in dollars
FWCOSTL4 (W) Total cost for UAN warehousing per year in dollars
DRYCPT4 (W) Storage costs for dry warehouses per ton
LIQCPT4 (W) storage costs for liquid warehouses per ton;
OPCOSTD4(W)=(0.5*COSTD4(W)*0.08);
OPCOSTL4(W)=(0.5*COSTL4(W)*0.08);
PVINTXD4 (W)=COSTD4(W)*0.025*40 ;
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```
PVINTXL4  (W)=COSTL4(W)*0.025*40;
MAINCOSTD4  (W)=COSTD4(W)*0.03*40;
MAINCOSTL4  (W)=COSTL4(W)*0.03*40;
FWCOSTD4  (W)= COSTD4(W)+OPCOSTD4(W)+PVINTXD4(W)+MAINCOSTD4(W);
FWCOSTL4  (W)= COSTL4(W)+OPCOSTL4(W)+PVINTXL4(W)+MAINCOSTL4(W);

EQUATIONS

COST_44  objective function_system4
CAPACDS4(W)  Observe storage capacity for dry fertilizers (DAP only)_system4
CAPACLS4(W)  Observe warehouse storage capacity for UAN fertilizers_system4;
COST_44..Z4=E=SUM((S1,W), X112(S1,W)*TRCOST(S1,W))+SUM((S3,W), X132(S3,W)
              *TRCOSTL(S3,W))+ SUM((W,F),X212(W,F)*TTRUCOST(W,F))
              +SUM((W,F),X232(W,F)*TTRUCOST(W,F))+ SUM((P1,F),DAACOST23(P1,F)
              *X312(P1,F))+ SUM((P2,F),LITACOST2(P2,F)*X322(P2,F))+ SUM(W,X412(W)
              *FWCOSTD4(W))+ SUM(W,X422(W)*FWCOSTL4(W))+ SUM(P1,DAFICOST23(P1)
              *X512(P1))+ SUM(P2,LIFICOST2(P2)*X522(P2));

CAPACDS4(W)..SUM(S1,X112(S1,W))=L=X412(W)*CAPWDS4(W);
CAPACLS4(W)..SUM(S3,X132(S3,W))=L=X422(W)*CAPWLS4(W);

MODEL SYSTEM44/COST_44, DAPSUP2,LIQSUP2,CAPACDS4,CAPACLS4,DAPDEM2,LIQDEM2,DAPBAL2
              LIQBAL2,APLOCD2,APPLYD2, APPLYL2, APLOCL2/;
SCALAR IT;
for (IT=1 to 150 , FWCOSTD4("CKING")=FWCOSTD4("CKING")-2000;
FWCOSTL4("CKING")=FWCOSTL4("CKING")-2000;
DRYCPT4  (W)=FWCOSTD4  (W)/CAPWDS4  (W);
LIQCPT4  (W)=FWCOSTL4  (W)/CAPWLS4  (W);

SOLVE SYSTEM44 USING MIP MINIMIZING Z4;

DISPLAY FWCOSTD4,FWCOSTL4,DRYCPT4, LIQCPT4,  Z4.L;

H1(W)=SUM(S1, X112.L(S1,W)*TRCOST(S1,W));H2(W)=SUM(S3, X132.L(S3,W)*TRCOSTL(S3,W));
H3(F)=SUM(W,X212.L(W,F)*TTRUCOST(W,F)); H4(F)=SUM(W,X232.L(W,F)*TTRUCOST(W,F));
H5(F)=SUM(P1,DAACOST23 (P1,F)*X312.L(P1,F)); H6(F)=SUM(P2,LITACOST2 (P2,F)*X322.L(P2,F));
H7(W)= X412.L(W)*FWCOST1(W); H8(W)=X422.L(W)*FWCOST2(W);
H9(P1)=DAFICOST23(P1)*X512.L(P1);
H10(P2)=LIFICOST2(P2)*X522.L(P2); H11(W)=H1(W)+H2(W); H12(F)=H3(F)+H4(F);
H13=SUM(W,H11(W))+SUM(F,H12(F));H14=SUM(F, H5(F))+SUM(F,H6(F));
H15=SUM(W,H7(W))+SUM(W,H8(W)); H16=SUM(P1,H9(P1))+ SUM(P2,H10(P2));
H17=H13+H14+H15+H16; H101=SUM(W,H11(W)); H102= SUM(F,H12(F));H103=H101/TAPAREA;
H104=H102/TAPAREA; H105=H13/TAPAREA; H106=H14/TAPAREA; H107=H15/TAPAREA;
H108=H16/TAPAREA;
H109=H17/TAPAREA;

DISPLAY H101, H102, H13, H14, H15, H16, H17, H103, H104, H105, H106);

*****************************************************************************************
** The feasibility of single location warehouse was analyzed using 30,000 dry storage ***
** and 60,000 liquid storage.  The storage capacity for small warehouses was zero      **
*****************************************************************************************
```

Linear Transportation Model

```
$OFFSYMLIST OFFSYMXREF OFFUPPER
options limrow = 0, limcol = 0;

SETS
S1 Sources of DAP fertilizers /ENID, PCTOOSA/
S4 Souces of ANHYDROUS fertilizer /W-WARD, ENID/

W warehouses /King, Okar, Yuko, Omeg, Pied, Wato, Henn/

F fertilizers /DAP, ANHYDROUS/

PARAMETER
SUPDAP (S1) Total supply of DAP in metric tones
 /
 ENID        3000000
 PCTOOSA     4600000/

SUPPANHY (S4) Total Suuply of ANHYDROUS AMMONIA in metric tones
/ENID        98000000
W-WARD       97600000/


TABLE  DISTDsTw (S1,W) distances from sources of DAP to warehouses
                King     Okar     Yuko     Omeg     Pied     Wato     Henn
ENID             40.3     48.4    72.30    52.93    61.90    66.49    20.95
PCTOOSA        151.32   142.40   135.47   166.33   129.26   186.53   150.15;

TABLE  TCOST(S1,W) DAP transfer cost per ton per mile from Sources to warehouses

                King     Okar     Yuko      Omeg       Pied      Wato       Henn
ENID            0.174    0.174    0.174      0.174     0.174     0.174      0.174
PCTOOSA         0.079    0.079    0.079      0.079     0.079     0.079      0.079;


TABLE  DISANYsTw (S4,W) distances from source of ANHYDROUS AMMONIA to warehouses
                 King      Okar     Yuko    Omeg     Pied    Wato     Henn
ENID             40.3      48.4    72.30   52.93    61.90   66.49    20.95
W-WARD           102.6     108.9   130.3   89.4     139.6   75.9     109.0;


TABLE  TCOSANY(S4,W) ANHYDROUS AMMONIA transfer cost per ton per mile from Source to
warehouses

              King    Okar     Yuko      Omeg       Pied      Wato       Henn
ENID          0.174   0.174    0.174      0.174     0.174     0.174      0.174
W-WARD        0.127   0.127    0.127      0.127     0.127     0.127      0.127 ;

Parameter
TRCOST(S1,W) DAP transfer cost per ton from Sources to warehouses
TRANHY (S4,W) ANHYDROUS AMMONIA transfer cost per ton from sources to warehouses;
TRCOST(S1,W)=TCOST(S1,W)* DISTDsTw (S1,W);
TRANHY (S4,W)=DISANYsTw (S4,W)* TCOSANY(S4,W);


Scalar
RATEANH3 ANHYDROUS AMMONIA application rate in metric tons per acre for application
system3 /0.05/
RATEDAP DAP application rate in metric tons per acre /0.027173913/;
```

```
Parameters
TFAREA (W) Total application area in each warehouse locations in acres
 /
 King      53899
 Okar      45709
 Yuko      38299
 Omeg      20033
 Pied      16498
 Wato      17254
 Henn      18233/

DEMANDAP (W) Total seasonal demand for DAP At the fields in tons_all systems
DEMANH3 (W) Total seasonal demand for ANHYDROUS AMMONIA at the fields in tons_system3;
DEMANDAP(W)= RATEDAP*TFAREA (W);
DEMANH3(W)=RATEANH3*TFAREA (W);

DISPLAY DEMANDAP, DEMANH3;


VARIABLES
Q1(S1,W) quantity of DAP shipped from source S1 to warehouse W in tones
Q2(S4,W) quantity of ANHYDROUS AMMONIA shipped from source S4 to warehouses
TR1 objective function for DAP transport cost
TR2 objective function for ANHYDROUS AMMONIA transportation cost ;
Positive variables Q1, Q2;

Equations
TRC1 Transport cost equation for DAP
TRC2 Transport cost equation for ANHYDROUS AMMONIA
DAPDEM (W) Demand equation for DAP
DAPSUP(S1) Supply equation for DAP
DEMAN(W) Demand equation for ANHYDROUS AMMONIA
SUPAN(S4) Supply equation for ANHYDROUS AMMONIA;
TRC1..TR1=E=SUM((S1,W),Q1(S1,W)*TRCOST(S1,W));
TRC2..TR2=E=SUM((S4,W),Q2(S4,W)*TRANHY (S4,W));
DAPDEM (W)..SUM(S1,Q1(S1,W))=E= DEMANDAP(W);
DAPSUP(S1)..SUM(W,Q1(S1,W))=L= SUPDAP (S1);
DEMAN(W)..SUM(S4,Q2(S4,W))=E= DEMANH3(W);
SUPAN(S4)..SUM(W,Q2(S4,W))=L= SUPPANHY (S4);

MODEL DAP /TRC1,DAPDEM, DAPSUP/
MODEL ANH3 /TRC2,DEMAN,SUPAN/

SOLVE DAP USING LP MINIMIZING TR1;
SOLVE ANH3 USING LP MINIMIZING TR2;
```

VITA

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Candidate for the Degree of

Doctor of Philosophy

Thesis: AN EXAMINATION OF ALTERNATIVE FERTILIZER TRANSPORTATION, WAREHOUSING AND APPLICATION SYSTEMS FOR AGRICULTURAL COOPERATIVES

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