A Multiobjective Mixed Integer Programming Application on the Design of a Material Supply System

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Abstract

This thesis presents the development of a multi-objective mixed linear programming model to design a material supply system for an ethanol manufacturing company. China has proposed a cassava development program to encourage cassava processing enterprises, mainly ethanol enterprises. These companies will build raw material production bases in mountain areas of Guang'xi province to help increase the revenues of local impoverished farmers. A cassava supply system responsible for raw material transportation from the farmers to the ethanol manufacturing plant is one of the essential strategies to ensure smooth operations of the company. The model is built to aid decision makers in selecting farmers for cassava supply and locating processing centers to serve farmers in order to construct the supply system. The locations of farmers and processing centers are determined to achieve the maximum poverty reduction and the minimum operation cost under the condition that cassava from all selected farmers meets the demand of the manufacturing plant. The maximum poverty reduction is accomplished by the largest poverty coverage and highest average income increase rate. The constraint method is applied to solve the model. The mathematical modeling formulation is coded in LINGO served by Excel data sheet. Trade-off solutions are presented to provide ample choices to decision makers on farmer selections and the processing center locations. The decision makers may choose to enlarge population coverage of the poor or increase their income increase rate, the cost will rise accordingly; or they may choose to reduce the cost with fewer covered poor farmers or with lower income increase rate.

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Chapter 1

Introduction

The objective of the thesis is to construct a material supply system using optimization techniques for a cassava based ethanol manufacturing company. It is motivated by an income-generating program of China. China proposes a program to foster cassava processing industries aimed at poverty relief for rural households in cassava planting areas. In this chapter, we present the background and briefly introduce the research problem.

1.1 Cassava

Before proceeding to the project description, we introduce some characteristics of cassava.

Cassava is a tropical woody shrub with an edible root. It tolerates drought and impoverished soils, even thrives on sandy-clay soils. Moreover, it has large yield with minimum input and is little affected by diseases and pests. Cassava is available all year round and possesses high flexibility with respect to the timing of planting and harvesting (Kay, 1973). Owing to these inherent characteristics of cassava, it has been an essential food source for people living in marginal land where cereals and other crops do not grow well and few alternatives exist.

Cassava is rich in carbohydrates, especially in starch. Fresh cassava contains about 30% starch and 1% protein. It is normally roasted and boiled as a meal in all the growing regions and also peeled, chopped into small pieces, dried and milled into flour for later consumption. Cassava is also a main constituent of livestock feed. In recent years, cassava has had considerable use as raw material in industry after being processed into starch. The applications of cassava based starch include: coating agent in paper coating, adhesive in wall paper; paste when drilling of oil wells or water wells; and use in the clothing finishing and printing process in the textile industry (Onwueme, 1978). There is a new trend to utilize starch to produce alcohol and ethanol. The former is used in cosmetics, solvents and pharmaceutical products. The latter is often treated as an alternative fuel of gasoline because of its clean burning property and is a renewable resource. The ethanol is not in replacement of gasoline but rather used as an additive of gasoline (the Government of Manitoba, Canada, 2004).

1.2 Cassava Development Status in Developing Countries

Due to its wide applications, cassava is not only a basic food source for farmers in developing countries in Africa, Asia, and Latin America but also an important cash crop that promotes rural development. After recognition of the cassava's economic value, many countries actively engage in cassava development and utilization. Cassava production has increased significantly in Africa in the last decades. However, as population grows with almost the same rate, cassava mainly serves as a staple food and is used domestically. In Nigeria over 90% of the cassava production is consumed. Over 71% of the farmers in Uganda grow cassava as a subsistence crop, 19% of the farmers grow the crop for cash and 9% of the farmers for other uses (Food and Agricultural Organization, 2001). Industrial utilization of cassava has been expanding in Africa recently. Cassava's potential as a foreign exchange earner is gradually explored by these countries (Hillocks, 2002).

In Southeast Asia, improved starch processing technology and varieties boost cassava output. Cassava rapidly changes its role from a food crop into an industrial material. In Vietnam, much of cassava is cultivated for starch processing and pig feed. Starch processing in Vietnam is performed both in rural households with traditional methods and by large, modern factories. Most of the starch goes to domestic food processing while some is used in the production of textiles, paper, and other products. Thailand has exported enormous amount of dried cassava to European countries to produce animal feed since the 1970s. About 50% of the country's cassava is used to produce starch and half of the total starch production is exported to Taiwan and Japan (Consultative Group on International Agricultural research, 1997).

Brazil grows 86% cassava in Latin America and is the second largest cassava producer in the world after Nigeria. Brazil pioneers in the utilization of cassava to produce ethanol. It has successfully mixed ethanol with gasoline to fuel automotive vehicles so as to lessen the dependence on foreign oil (Cock, 1985).

The world trend of cassava production is an increasing industrial use of cassava roots, mainly processed into starch. Research on cassava utilization and market is carried out in developing countries with the purpose to help cassava-planting farmers to earn a living. If a sustainable strategy for cassava is developed, there will be a significant impact on poverty reduction of farmers in these countries.

1.3 Cassava Utilization as an Income Generation Strategy in China

China is actively seeking a way to make use of cassava to improve farmers' lives too. Cassava is widely grown in southwest China and covers several provinces including

Guangdong, Guang'xi, Yunnan and Hainan. Guang'xi has largest cassava production in the country. In China, the utilization of cassava attracts growing attentions and strategies to make use of cassava as a way of income generation are developed.

1.3.1 The Need for Cassava Development Strategy

The adverse land condition of Guang'xi rules out many food crops and leaves cassava a competitive crop for plantation. Guang'xi is located in a mountainous area. It has limited flat land available to basic cereals such as wheat and rice which usually require large square or belt areas. Soils are very infertile and acid; while many areas are quite dry (Tian *et al*, 2001). Hence, much of the agricultural effort goes into industrial crops suitable to the local conditions. Cassava is a competitive candidate because of its inherent characteristics. Guang'xi has a subtropical climate suitable for cassava growth and local farmers have a long history of cassava cultivation (Guang'xi People's Government, 2003).

Guang'xi is one of the poorest provinces in China. According to an economic report of the Ministry of Agriculture of China (Huang, 2003), in 2001, 5.08 million farmers have net yearly incomes below 1,000 Yuan (200 CAD) per capita. They comprise 13% of total farmers in Guang'xi province. These farmers are living in a subsistence level and food security cannot be ensured. There are another 8.9 million farmers in Guang'xi above the subsistence level but not far above and they have a chance to fall back. As farmers compose of 87.1% population of Guang'xi province (Guang'xi People's Government, 2003), their poverty relief is the key to the improvement of the living conditions of the whole province. The development of strategies to assist local farmers to overcome poverty and to raise their living standards is continuing to be a focus of Guang'xi government.

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*Yuan is Chinese currency unit and CAD is abbreviation of Canadian Dollars. 1 CAD ≈ 5 Yuan.

Witnessing the importance of cassava in industry, the Guang'xi government plans to develop cassava industries so as to take advantage of local resources and enhance farmers' revenues. Using cassava to produce ethanol is a promising direction. The unprecedented development speed of China brings huge consumption of resources including oil. The nation's oil consumption has leapt to the third in the world. It surpassed 100 million tons in 1978, exceeded 150 million tons in 1996, then remained over 160 million tons for five successive years, ranking the fifth in the world (People's Daily, 2002). The blend of ethanol into gasoline reduces oil consumption and thus eases the strain placed on energy demand. Equally important, ethanol gasoline contributes to cut greenhouse gas emissions that are responsible for global warming. The technology of transforming cassava into ethanol is mature in the world market and the trial test of fuelling vehicles with ethanol has already begun in China. In addition to the increased demand from starch processing industry, cassava is expected to be in high demand in the energy market.

The poverty condition of Guang'xi makes cassava development an urgent need and the market offers a favorable opportunity. Cassava itself has additional advantages as an economic crop in Guang'xi. It has less demand on plantation technique. Thus it remains accessible to most farmers in Guang'xi where the general education level of farmers is low. Farmers can manage it with necessary technical assistance. Besides, it does not require frequent attendance and intensive care, unlike some fruits or vegetables during their growths; time is saved for farmers to conduct other agriculture activities. Finally, as it can be planted in corners or slopes, it does not occupy the limited space for cereals and is economically viable. After synthesizing many factors, the Guang'xi government decided to develop cassava-based ethanol industries as an income generating strategy.

1.3.2 Cassava Development Program

In 2000, a program called "Development of Sustainable Cassava Industries" was launched in Guang'xi province, China (Administration Office for Guang'xi New and High Technology, 2000). The objective of the program is to increase local farmers' income by developing cassava processing industries. The implementation mode is "industrial companies + crop bases + farmers". That is, to build manufacturing companies which process cassava into profitable industrial products, mainly ethanol; to establish crop cultivation bases to assist farmers in cassava planting, whose task includes introducing good strains of seeds and imparting planting technique for high yield of crop; and to encourage farmers to sign contracts with the companies to grow cassava meeting the ethanol production need. Both farmers and the companies gain benefits through this chain mode. On the one hand, this mode solves the sales problem for farmers and provides farmers steady income. Fresh cassava is difficult to store and often deteriorates very quickly within 48 hours after harvest (Cock, 1985). In the past, farmers suffered loss due to lack of sales channels and the selling price for cassava varied swiftly with seasons. On the other hand, the companies achieve sufficient and qualified material supply. In addition, the manufacturing companies provide work opportunities for farmers nearby. Methane from ethanol production process can be utilized for rural energy supply.

The establishment of an ethanol manufacturing enterprise with a yearly capacity of 500,000 tons is the core project in the program. It composes of five manufacturing plants each with 100,000 tons. About 860 km^2 land area and around 100,000 farming families (average 5 persons in a family) are involved in the full-fledged program. The project is organized by two parts of building ethanol manufacturing plants and cassava processing centers:

- Build ethanol manufacturing plants in Chongzuo district of Guang'xi province. The manufacturing plants receive cassava from processing centers to produce ethanol. Meanwhile, they deliver proteins to the whole area and mud to the processing centers. Proteins are refined products from ethanol manufacturing residues and sold as high concentration poultry feed. Mud is another side-product. The manufacturing plants delivered it to the processing centers to produce base fertilizer specifically for cassava crops.
- Build cassava processing centers in cassava planting areas. The cassava processing centers are responsible for cassava seed cultivating, cassava collection from farmers upon harvest and processing fresh cassava into flour. The collected cassava is dried after cleaning, peeling, crashing and then put into storage to be sent to the manufacturing plants. The processing centers also handle mud from the manufacturing plants. The mud is processed with other materials as base fertilizer and sent to contracted farmers during cassava planting season. Moreover, the processing centers provide technical assistance to the farmers to ensure high yield of cassava.

1.4 Research Problem

The first stage of the project to establish an ethanol manufacturing plant with 100,000 tons was put into agenda by local government in 2001. An existing ethanol manufacturing plant in Chongzuo is going to be renovated instead of building a new one. In addition to ethanol processing techniques, the government wants a number of strategies to achieve efficient operations of the manufacturing plant. These strategies include material supply, production planning and ethanol product distribution. A cassava supply system that deals with cassava collection from farmers and transportation to the manufacturing plant is one of the essential strategies to be studied.

A 100,000 ton manufacturing plant requires 780,000 tons of fresh cassava to meet the production capacity (Guilin University of Electronic Technology, China, 2002). Such huge amount is produced by farmers dispersed in cassava planting areas. High investment incurs on the transportation of cassava from farmers to the manufacturing plant and a well-organized supply network is needed for optimal investment.

In this thesis, we use optimization tools to establish a cassava supply system at a strategic level. A cassava supply system is composed of farmers, processing centers and the manufacturing plant. Both cassava and the manufacturing by-product, mud, are shipped between farmers and the plant via processing centers in the network, which has an effect on the cost composition. In order to construct the system, decisions concerning the locations of the farmers and processing centers as well as quantities of material flows have to be made. The processing center location problem and transportation sub-problem are thus formulated to complete the task.

In the processing center location problem, a multi-objective mixed integer programming model is developed to select farmers for cassava supply and to locate the processing centers. The multi-objective intends to select farmers on the basis of income generation and operation cost so that both the program goals can be reached and the enterprise is satisfied for cost-saving. In addition to location/allocation decisions, the model determines the supply quantity from each selected farmer. The constraint method is selected after compared with other methods to solve the model and implemented in LINGO, an available off-shelf optimization software.

In developing the model, we assume that all materials are shipped in straight line trips in the network except the protein feed. As the protein feed is distributed among farmers by trucks traveling in tours, a vehicle routing model is formulated to plan the delivery routes in the transportation sub-problem. We applied the Clarke and Wright algorithm to solve the vehicle routing model and coded it in C++.

As the result of this study, large poor farmer population with high increase of their average income and less transportation cost is selected for cassava supply. The processing centers are located to serve their covered farmers and in transferring materials from and to the manufacturing plant. This result can be used by the local government for final cassava supply system configuration. With location and material shipment information, the cassava supply system can be established and operate in an efficient way.

1.5 Organization of the Thesis

The thesis is organized into 5 chapters including the introductory chapter.

Chapter 2 provides the review of the literatures related to the problems. In chapter 3, we formulate the research problems and develop a multi-objective MIP (mixed integer programming) model for optimal locations of processing centers. A vehicle routing model is developed thereafter to establish a vehicle dispatching schedule for protein feed distribution. Both models are solved in chapter 4. The constraint method is applied to solve the processing center location problem. The trade-off solutions among the objectives are discussed and plotted. The result intends to assist decision makers for establishing the processing centers. After the network is set up, the Clarke and Wright saving algorithm is applied to solve the vehicle routing problem. Solution is to determine the number of fleets assigned and the trips traveled by each fleet. A complete view of the structure and operations of the supply system is then discussed. Chapter 5 presents conclusions and future work of this research.

Chapter 2

Literature Review

The problem we studied in the thesis is the distribution system design problem and is further divided into two problems: processing center location problem and protein feed distribution problem. We review literatures on distribution network design problems, facility location problems and vehicle routing problems. Cassava related research currently conducted in China is introduced in the end of this chapter.

2.1 Strategic Design of Distribution System

Smooth and efficient material flow channels bring enterprises faster, more flexible reactions to market demand with lower cost. As logistic cost becomes a major part of the total product costs, companies today are forced to reduce logistic cost. Reconfigurations of logistic systems including raw material supply and final product distribution have been conducted by many companies. One of the effective ways to analyze and evaluate a distribution network performance is to formulate a linear mixed integer programming (MIP) model. In the MIP model, material flow is optimized based on cost or profit. The MIP models have been successful in the design of distribution networks as indicated by case studies discussed below.

Sery *et al.* (2001) developed a mixed integer linear programming model to reconstruct the distribution system of BASF Corporation. BASF Corporation is an American based subsidy company of BASF Group, one of the world's leading chemical companies. It offers a range of chemical and chemical-related products to customers from over a hundred shipping locations. Some products were directly shipped from plants or contracted companies and others were shipped via distribution centers (DC), public and private warehouses. In order to overcome low efficiency distribution operation, a mixed integer programming model is developed to evaluate and redefine the number and locations of DCs as well as corresponding material flows. Variable costs were considered in the model including production costs at plants, transportation costs from plants directly to markets, from plants to DCs and from DCs to markets, handling and storage costs at the DCs and penalty costs for any demand shortage. Alternate configurations were founded by the model and both improved delivery times and lower costs were observed from the results with reduced number of DCs. BASF modified the North America distribution system accordingly and the revised distribution system resulted in 15% improvement in the volume of goods delivered next day.

Sankaran and Raghavan (1997) applied a binary integer programming model to optimize the bottling propane (referred as liquefied petroleum gas) distribution from bottling plants to dealers. Decisions on the locations and long-run sizes of bottling plants were made by minimizing the fixed costs and costs of assigning dealers to plants. The assignment cost is summation of transportation cost, bottling cost, annualized capital cost of bottling cylinders and negative terms of saving from sales tax exemption for liquefied petroleum gas sold to dealers within the same states.

A two-echelon distribution network design problem was tackled by Robinson *et al.* (1993) at DowBrands, Inc. Conceptually, a multi-echelon network comprises of hierarchically linked distribution centers or warehouses between the material flow origins such as plants and the destinations such as customers. The multi-echelon network at DowBrands consisted of central distribution centers (CDCs) in the primary level and satellite regional distribution centers (RDCs) dispersed in the second level. The products were distributed either through CDCs or through RDCs to customer zones but a RDC must attach to a CDC for service. The formulated mixed integer programming model identified locations of CDCs and RDCs, assigned RDCs to CDCs and decided the shipment quantity from each facility to customers at the same time.

When a distribution system is extended to integrate material procurement, supply and manufacturing into its network, a supply chain is formed. Supply chain optimization has been extensively studied in recent years with theoretical success both in model formulation and solution techniques. The redesign of supply network of dairy products in Nutricia Dairy & Drinks Group, Hungary is an illustrative example. Wpuda *et al.* (2002) applied a mixed integer linear programming model to optimize the supply network of Nutricia Dairy & Drinks Group in Hungary. The supply network of Nutricaia is organized by small farms, milk collecting points, dairy product plants, distribution centers of finished goods and customers. The optimization covers all the activities in the network including milk collection, milk transportation from farms to plants, milk reception, dairy product manufacturing, inter-transportation of semi-finished products as well as finished products transportation from plants to sales regions. The model made an optimal plan for the supply chain operation after defining the locations of plants, the amount of multiple products produced in each dedicated plant and shipped to distribution center. The model is inline with traditional location/allocation models, with modification concerning inter-transportation of semi-finished products between plants.

The above literatures revealed that most of distribution system designs involved decisions on facility locations. Facility location is one of the key elements along with inventory, transportation for constructing a distribution network. In the following, we review the basic facility location models including multi-objective models and discussed some extensions from basic models.

2.2 Facility Location Models in Distribution System Design

The definition of facility location problem given by Beasley (2003) is: given a set of facility locations and a set of demand nodes, or customers, served by the facilities then:

- which facilities should be used
- which customers should be served from which facilities so as to minimize the total cost of serving all the customers.

The facility location problems can be classified into deterministic vs. stochastic and static vs. dynamic problems for their different characteristics to deal with real world complexities. A deterministic and static problem locates facility in one point of time and with known demand. A dynamic problem extends to include multiple periods of time. A stochastic problem puts uncertain demand into consideration. In the deterministic and static domain there are three basic types of problems: median (p-median) problem, covering (set covering, maximal covering) problem and center (p-center) problem. These problems, either minimizing the distance between the facilities and the demand nodes or maximizing the covered demand, restrict the open facilities to be a fixed number such as p. The fixed charged facility location problem, also called as the simple plant location problem, relaxes this constraint and determines the optimal number and locations of the facilities. This type of problems can be further divided into "capacitated facility location problems" and "uncapacitated facility location problems", depending on capacity constraints on facilities. A quick acquaintance of classification of the facility location problems and solution techniques can be found in Brandeau and Samuel (1989). Daskin (1995) introduced the fundamental concept, linear formulations, solution algorithms and applications of deterministic facility location problems in detail. Aiken (1985) reviewed different types of facility location models. A latest review of current research in this area was provided by Owen and Daskin (1998). In this paper, the static and deterministic location models such as median, covering and center problem models were presented and discussed. Dynamic models were highlighted and research problems incorporating stochasticity to capture real-word uncertainty were discussed. Our review is concentrated on models in deterministic and static domain and we divide the facility location models into single objective function models and multi-objective function models.

2.2.1 The Single Objective Facility Location Models

The *p*-median problem is to find the locations of *p* facilities so as to minimize the total distance between demand nodes and facilities. Erkut *et al.* (2000) used a *p*-median model to locate TransAlta Utilities (TAU) service centers. TAU is Canada's largest publicly owned electric utility company and offers services including bill payment, customer request repair and power line patrol via service centers. TAU removed the bill payment service from service centers and rearranged centers as call centers to reduce cost. As the call centers should be close to the customers to offer rapid response, the selection criterion of call centers is the minimization of sum of the demand added distance. In the service delivery network, each demand point is also a candidate site of a call center and the optimal number of call centers in the distribution network depends on the trade-off between facility costs and transportation cost. The same network structure was adopted in our thesis on the design of the cassava supply system.

There are two types of covering models in facility location problems which are the set covering and the maximal covering models. The main difference between these two types of models is that coverage is required or optimized (Owen and Daskin, 1998). In both models the facility has the maximal service distance and it only serves demand nodes within that distance. The set covering is to locate the minimum number of facilities to ensure all demand nodes are covered. The maximal covering problem is to maximize the total demand for service by the fixed number of facilities. These two covering models have wide applications such as ambulance location and relocation (Brotcorne *et al.*, 2003), location of fire stations (Schreuder, 1980), location of industrial centers (Swerysey and Lakshman, 1995) and other problems requesting certain level of population or demand coverage. Chung (1986) provided a review of the maximal covering models and introduced variations and various applications of them. Current (1992) applied both set covering and maximal covering models to evaluate locations of the emergency warning sirens in a Midwestern United States city. Two types of siren with different costs and covering radii were available. The city was resembled by grid form of which demand nodes and potential sirens were located in the intersection. The set covering model was formulated first to locate sirens to cover all demand nodes with minimum cost. Because the cost may exceed the budget for complete coverage, the maximal covering model was given as an alternative to maximize the siren coverage within budget limit. The model was solved using commercial software and a more efficient solution from scenario analysis was identified after comparison with the solution from manual planning. The solution result was used to determine the final siren scheme to be deployed.

The explorations on the fixed charge facility location models are rich in literature. Revelle and Laporte (1996) described different versions of these models. Karabakal *et al.*

(2000) combined the fixed charge facility location model and a simulation model to locate vehicle distribution centers for Volkswagen. The objective of the model was to minimize the fixed cost of the facilities, the transportation cost and vehicle cost. These costs were subjected to the vehicle flow conversion and the maximum and minimum capacity requirement of the facilities. The vehicle distribution process was streamlined after determination of different types of distribution center locations and the facility for each center. The simulation model was applied to consider dynamic and stochastic elements in the system.

2.2.2 The Multi-Objective Facility Location Models

In some cases the single global objective, cost minimization, is not sufficient to address real world needs. Each type of business has its own concerns or criteria to select the desired locations in addition to cost consideration. For instance, the maximal access to local benefits is required in locating ambulance, hospital and other public services. Enhancement of customer responsiveness may become the secondary factor after cost for firms to open distribution centers or chain stores. Environmental pollution reduction is frequently addressed in the obnoxious facility location problem such as locating a chemical plant. As it is difficult to represent these qualitative objectives in forms of cost, such as penalty cost in dollars, single objective models may not be appropriate. Multi-Criteria Decision Making (MCDM) is a widely used tool to deal with such situations. Current *et al.* (1990) summarized multiple criteria in the facility location models and classified these criteria into four general categories: cost minimization, demand oriented, profit maximization and environmental concerns.

Nozick and Turnquist (2001) developed a multi-objective integer programming model to locate facilities from potential sites to minimize facility, inventory and transportation costs and to reduce uncovered demand. The minimization of uncovered demand within a specified coverage distance intends to provide a high level of customer responsiveness. It contradicts the objective of overall cost minimization since "providing fast, reliable delivery of products to retail outlets may be met by a large number of distribution centers conveniently located" and a large number of distribution centers imply high operation costs. Thus, there is a fundamental trade-off between facility costs and customer responsiveness. The problem was solved by the weighting method. A weight number was attached to the demand objective to transform the multi-objective model into a single objective model. By varying the values of the weight, a variety of trade-off solutions were identified in the case study for US automotive industry.

Jayaraman (2000) addressed the concern of customer responsiveness by minimizing distance for demand nodes to access facilities. The formulated multi-objective mixed integer programming model contained three objectives which are the minimization of fixed costs, minimization of variable costs and minimization of weighted demand distances between demand points and facilities. The decision to minimize fixed cost to open facilities is in conflict with the decision to minimize the total distance. While the distance minimization objective selects all the facilities as close to the markets as possible in order to shorten delivery distance and implies a large number of facilities, the objective of fixed cost limits the facilities to the fewest. These objectives are frequently treated as a single objective in the fixed charge facility location problem. Jayaraman divided them to explore their relationship in detail. The trade-off solutions among the different objectives were gained from the revised weighting method, NISE, and demonstrated using value paths. Ehrgott and Rau

(1999) investigated the relationship of cost versus service time. A bi-objective mixed integer programming model was developed to optimize a two stage distribution network and the service criterion was represented by weighted average delivery time. Different scenarios were evaluated. For each scenario, the cost was minimized first and the delivery time was computed for that optimal cost solution. The results reveal that better service can be achieved through higher cost. The final decision represents a compromise between the two criteria. In the model, a nonlinear transportation cost was developed for some cases and similar results were yielded to the cost in the simple linear configuration.

In the public facility location problem the covering objective always presents in the model for maximum access to the facilities. Flynn and Ratick (1988) utilized the maximal covering formulation to develop a bi-criteria integer programming model to allocate air services to communities in a region. In addition to the population coverage objective, a second objective to minimize the system wide cost was employed. The problem was solved by the constrained method. Specifically, the population coverage objective was maximized while restricting the total cost objective to be less than or equal to different cost values. By using the multi-objective approach, the trade-offs between the two conflicting objectives of coverage and cost can be explored. The service locations from a sample study of a small community air service in North Dakota, South Dakota, Massachusetts, were plotted. Eaton *et al.* (1988) included the set covering model in the multi-objective analysis of locations for ambulance service in Santo Domingo. The set covering model determined the minimum number of facilities needed to cover the whole population. The other competing objective maximized multiple coverage of demand to ensure well response during period of high volume of emergency calls. The model can either be solved sequentially or be converted into a single objective model by minimizing weighted sum of the two objectives.

Goal programming is a powerful technique to solve multi-criteria location problems. Badri *et al.* (1998) presented a goal programming model to locate fire stations. The number and locations were evaluated by eleven criteria which were defined as 11 goals. Besides the cost related goals, other goals consisted of attaining largest service areas, attaining the targeted number of fire stations, minimizing average and maximal response distances, minimizing average and maximal response time, minimizing service overlaps and some other customer specified goals. After defining the priority of the goals, optimal locations of fire stations were identified with different targeted numbers. Goal programming is an effective method for solving problems with over three or more objectives.

2.2.3 Variation and Extension of Facility Location Models

Numerous extensions of the basic facility location models have been studied by researchers. We describe some representative models and introduce the current trend of facility location research.

Koksalan and Sural (1999) formulated a multiperiod facility location model to locate plants which should be built in the same sites but in different years. The multiperiod location model answers the question of when to establish a certain amount of productive capacity at a certain location. It is featured by including the time period as one of the indices to each decision variable. In Koksalan and Sural's work, products were produced to meet demands of different years. Plant capacity and transportation balance were met on the yearly basis and the costs were summed by year. The objective function to be minimized was the total discounted transportation and fixed cost. The multiperiod facility location models are also called the dynamic location models. It was solved by an available optimizing software.

Hwang (2002) formulated a stochastic set covering model to determine the minimum number of warehouses so that the probability of each customer to be covered was not less than a critical service level. The service level was measured by logistic cost which was treated as function of time. Uncertainty was thereby introduced to the problem.

A given network is assumed for locations of facilities in most facility location problems. Nevertheless, design of a transportation infrastructure such as a railway system in a city and an airline network requires link construction between facilities and demand sites to be a new network. The network design problem arises to simultaneously locate facilities and build the links. The cost of the network problem comprises a transportation cost and a fixed link installation cost. Melkote and Daskin (2001) utilized the classical capacitated facility location model to address a network design problem. The problem was formulated as a mixed integer programming model and both single product and commodity specific formulations were presented. The model minimized the fixed facility cost, fixed link cost and material flow cost subject to link conservation, facility capacities and other valid inequality constraints. The authors concluded that the link investment cost and transportation cost decreased when capacity constraint was imposed after comparison of the uncapacitated model with the capacitated one.

Cost or profit optimization is frequently used for facility location selection and distribution system design. However, it is only based on company oriented logistic thinking. Korpela and Lehmusvaara (1999) proposed a novel idea to deal with warehouse location problem from the customer driven approach. A qualitative factor, customer-specific priority, was taken as an objective to be maximized in the formulated mixed integer linear programming model. This priority describes how well a certain warehouse operator is expected to satisfy a certain customer's performance requirements. The priority of each alternative warehouse operator was determined through Analytical Hierarchy Process (AHP). The model is more suitable to evaluate and select the alternative warehouse operators than to find the specific warehouse locations.

Companies in today are actively engaged in expansion into international markets. Global expansion offers access to new markets and opportunities to utilize economies of scale (Hoffman and Schniederjans, 1994). The globalization business trend makes the global facility location problem an interesting topic. Arntzen *et al.* (1995) designed a global supply chain model to streamline a production, distribution and vendor network. The model was a large mixed integer linear programming model. Cost was composed of fixed and variable production charges, inventory charges, distribution expenses via multiple modes, taxes, duties and duty drawbacks. Including duties and duty drawbacks into cost composition differs the global facility location model from other facility location models. The model minimizes a weighted combination of total cost and activity days to make decisions on locations of facilities, production, storage and shipment quantities of different products in different facilities and different time periods.

There are many other types of facility location problems emerged or studied intensively recently. They include location of competitive facilities and combined location routing problems. In summary, facility location models are complicated with following factors: multiproduct, multidepot, multiechelon and multiperiod. Researchers extend the basic facility location models to incorporate the real world complexities when formulating the models. We note that the integer linear programming formulation is used to solve most problems. This is due to the fact that the integer linear programming offers a relatively simple approach but satisfying performance on strategic facility location analysis. Also, it provides valid insights into distribution systems.

2.3 Vehicle Routing Models

A vehicle routing problem intends to determine for each vehicle, which of the customers will be visited and what route will be followed so that the total delivery cost is minimized. It assumes that each customer has demand far less than truck capacity and a fleet travels in a single trip to satisfy all the customer demand in the route. Golden *et al.* (1977) formulated both single depot and multidepot vehicle routing problems. Several different subtour elimination constraints were proposed and compared. The number of vehicles and their delivery routes are determined by truck capacity and route time constraints. The models only have zero-one variables. The continuous flow variables were included in the vehicle routing model formulated by Nambia (1981). Nambia's model is efficient to deal with the complicated case in which more than one product is in the routing and these products are both loaded and uploaded in the demand points since the model clearly states the shipment quantity of each product in the link.

There is one type of vehicle routing called the period vehicle routing problem. In the period vehicle routing problem, a fleet travels several times or in combination of the days in a week to the customers. The customer demand is satisfied on the weekly basis not on any individual days. The period vehicle routing model can make full use of truck capacity compared with the standard vehicle routing model and its merit is illustrated by Bell *et al.* (1983). In his model, optimal routes were selected, departure time (assume integral) of each route was specified and amounts to be delivered to each customer during each time period were determined.

Incorporating vehicle routing models into the facility location problem can greatly reduce the cost (Min *et al.*, 1998). In traditional facility location problems, transportation is assumed straight line trips from facilities to demand points. It omits the situation that the trucks may travel in tours to deliver commodities and the transportation cost thereafter can be reduced greatly. The location routing model puts such situation into consideration and optimizes cost by locating facilities and planning the delivery routes originating from facilities simultaneously. Perl and Daskin (1985) put forward a multi-depot location routing model and solved the model using a decomposition method. The original location routing model was divided into three submodels: the multi-depot vehicle dispatch model, the warehouse location allocation model and the multi-depot routing allocation model. The 1st submodel was to gain a set of routes each linked to a potential warehouse under the assumption that all potential distribution center sites were used. Then the linkages of delivery routes to the warehouses were broken up and each route only consisted of ordered sequences of customers. With the unconnected delivery routes and the candidate warehouses the 2nd submodel located the warehouses and assigned routes to the warehouses. After the warehouses were determined, the final submodel was employed to route customers again but with known warehouses. Beginning with the second model, the result of each model was compared to the previous one for the same or improved results. The iteration stopped when a certain level of improvement was reached.

2.4 Cassava Research in China

China pays great attention to cassava's potential as an industrial material and ethanol is one of such materials. As stated before, utilization of cassava to produce ethanol can alleviate fuel shortage in China. Large scale ethanol production can bring invigoration to local industries and thus farmers' income can be increased by growing cassava for these industries. But some factors hinder cassava ethanol from becoming an economic product such as high prices compared to the gasoline and the negative environmental effect caused by ethanol production. The strategy of cassava ethanol production needs to be evaluated in light of these factors. The current research on industrial use of cassava in China concentrates on life cycle assessment of ethanol derived from cassava. This study predicts the cassava ethanol product life length from economic, energy consumption and environmental pollution aspects. The research began in 2002 and is conducted by scholars from Shanghai Jiaotong University and Guilin University of Electronic Technology, China. A cost model was built for ethanol fuel life cycle analysis (Zhuang *et al*, 2003). The research is continuing at the time of wring this thesis.

Chapter 3

Model Formulations

In this chapter, we formulate the research problem and develop a mixed integer linear programming model to solve the problem.

The problem studied in this research is to design a cassava supply system to meet cassava demand of a manufacturing plant. A new ethanol manufacturing company is going to set up several processing centers to collect the raw material, cassava, from local farmers. The cassava supply system is composed of a manufacturing plant, several processing centers and the farmers. The system requires transportation of cassava, mud and protein feed, three types of materials in different time periods. Cassava is usually harvested, collected from farmers and transported to the processing centers from November to January every year. Because fresh cassava contains much more starch than dried one, the manufacturing plant prefers fresh cassava for ethanol production. In these 3 months, around 25% cassava in total collection is transported to the manufacturing plant after preliminary processes of washing and peeling in the processing centers. The rest 75% collected in the harvest time is processed into dried flour which is in reduced size and weight and put into storage for later use throughout the whole year. Mud, the production left-over, can be used as a base fertilizer for cassava crop. It is transported from the manufacturing plant to the processing centers regularly, stored and delivered to the contracted farmers upon planting time in late April or the beginning of May. Protein essence is another side-product refined from the ethanol product and used to produce protein feed. Protein feed is distributed among the farmers. A store in each town is planned to be set up to sell the feed to farmers all over the area.

We formulate the processing center location problem to select farmers for cassava supply, to locate processing centers and to allocate the selected farmers to the processing centers in order to construct the system. A vehicle routing model is formulated in the transportation sub-problem for efficient route planning of protein feed distribution.

3.1 Processing Center Location Problem

3.1.1 Problem Definition

In the considered cassava growing region, far more cassava crops can be supplied by local farmers than those needed for ethanol production, thus not all farmers in the area are engaged in the program. We select both farmers from potential groups and the processing centers from potential sites and allocate farmers to processing centers.

Definition of potential sites

We first define potential farmer groups and processing centers. In solving our problem, farmers are grouped to reduce problem sizes. The number of farmers will be large if each farmer family is regarded as a unit to be covered. In view that rural farmers are divided into and administrated by towns, the farmers belong to a town are regarded as a group and cassava crops are collected from farmers based on towns.

The potential sites of processing centers are also defined to be located in towns. Farmers scatter in rural countryside and towns are the centers for them to have a trade. Town based processing centers facilitate cassava collection from farmers and technical assistance to the farmers. A town is also an outlet to a city or other outside fields. Roads are available to connect towns and convenient for trucks to commute between the manufacturing plant and the processing centers.

After potential farmers and processing centers are identified, a candidate cassava supply network is formed with both supply nodes and facility nodes represented by towns. The manufacturing plant is also located in one of the towns. Farmers are then selected to plant cassava to satisfy the ethanol production need and the processing centers are located to collect cassava from farmers.

Multi-objectives of the problem

In solving our problem, multiple criteria are applied to select farmers from potential groups and to allocate them to processing centers for cassava supply.

Farmers are selected according to the program goal of income generation since it is a government sponsored program. Income generation intends to increase local farmers' income so as to relieve as many farmers as possible from poverty-stricken living conditions. This goal can be expressed by two objectives: covering more farmers and raising those farmers' income. Hence, the Maximum Population Coverage and the Highest Average Income Increase Rate of farmers are the two criteria which are also two objectives of the model. These two types of information are frequently found in annual reports of the government or in broadcasting news and used to present the achievements of government actions on poverty reduction. Considering that income disparity exists in the region, we target our income generation objectives especially to the impoverished farmers. They are the farmers whose average yearly income is equal to or below a certain poverty level. The two objectives of the problem finally turn to be the Maximum Poverty Population Coverage and the Highest Average Income Increase Rate of the Poor. The farmers' income increase is achieved by selling cassava to the manufacturing plant.

These two objectives aim at poverty reduction and select farmers from income generation point of view. However, considering these two goals only may bring higher transportation cost to the manufacturing plant since poor farmers may not necessarily be close to the plant. As profit gain is a primary goal for an enterprise to survive, we put forward the third objective of the Minimum Total Cost, mainly fixed facility cost and transportation cost, in addition to the above mentioned two objectives to identify farmers covered in the program.

The processing centers are sited in the course of the manufacturing plant and the farmers. Their locations are balanced by the facility cost and transportation cost.

We summarize the processing center location problem below.

Given a set of potential locations of processing centers and farmers, find the optimal number and locations of farmers to supply cassava crops to an ethanol manufacturing plant and determine the locations of the processing centers to serve farmers such that both the Poverty Population Coverage and the Average Income Increase Rate of the Poor are maximized and the Total System Cost is minimized. The cost consists of fixed costs of the processing centers and transportation cost from the manufacturing plant to farmers via the processing centers.

3.1.2 Model Formulation

The problem is formulated as a multi-objective mixed integer programming model. In the model, a processing center covers many farmer groups but a farmer group belongs to exactly one processing center if it is covered. The model uses one year as the time period.

We introduce assumptions in formulating the model and define the decision variables and parameters of the model. For notation convenience, we refer a farmer group as a "supply point" and a processing center as a "warehouse".

Assumptions

- The cassava income of the farmers before they join the program is omitted. The income increase brought by cassava to farmers only comes from the profit earned by selling cassava to the manufacturing plant. This assumption is reasonable since without in-depth processing by large scale industries, cassava is a low profit food product. In addition, the government concerns the effect of establishment of manufacturing enterprise on the improvement of the local farmers' income.
- The transportation costs of cassava and mud are linear functions. They are proportional to the amount and distance traveled.

Notation

$i = 1..N$ candidate warehouses.

$j = 1..N$ candidate supply points.

N : the total number of nodes (the number of candidate warehouses is same as that of supply points, both of them are equal to N).

Variables

$$X_i = \begin{cases} 1 & \text{warehouse } i \text{ is selected,} \\ 0 & \text{otherwise.} \end{cases}$$

$$Y_j = \begin{cases} 1 & \text{supply point } j \text{ is selected,} \\ 0 & \text{otherwise.} \end{cases}$$

$$Z_{i,j} = \begin{cases} 1 & \text{warehouse } i \text{ serves supply point } j, \\ 0 & \text{otherwise.} \end{cases}$$

$STOR_i$ = amount of cassava stored in warehouse i (ton).

XC_j = amount of cassava collected from supply point j (ton).

M_i = amount of mud stored in warehouse i (ton).

XM_j = amount of mud shipped to supply point j (ton).

Parameters

$$l_j = \begin{cases} 1 & inc_j \le pl, \\ 0 & \text{otherwise.} \end{cases}$$

inc_j = average income of the population in supply point j (Yuan).

pl = the poverty level (Yuan).

p_j = population of the supply point j.

d = cassava demand in the manufacturing plant (ton).

$\overline{\alpha}$ = the upper bound of cassava demand in the manufacturing plant (in percentage).

cap_j = the maximum amount of cassava can be produced from supply point j (ton).

col = the minimum amount of cassava should be collected from a supply point once it is collected (ton).

$mprod$ = amount of mud produced in the manufacturing plant (ton).

pro = profit earned by selling one ton cassava (Yuan per ton).

f_i = fixed cost of warehouse i (Yuan).

c = transportation cost (Yuan per km per ton).

sc = cassava storage cost (Yuan per ton).

$ds_{i,j}$ = distance between warehouse i and supply point j (km).

dp_i = distance between warehouse i and the manufacturing plant (km).

r = conversion factor that translates one ton fresh cassava to dried flour.

The Model

Objectives

Maximize the poverty population coverage

$$\textbf{Max}\ \ Z_1 = \frac{\sum_{j=1}^{N} l_j Y_j p_j}{\sum_{j=1}^{N} l_j p_j} \tag{1}$$

Maximize the average income increase rate of the poor

$$\textbf{Max}\ \ Z_2 = \frac{pro \sum_{j=1}^{N} l_j XC_j}{\sum_{j=1}^{N} l_j Y_j p_j inc_j} \tag{2}$$

Minimize total cost including fixed cost and transportation cost

$$\begin{aligned}\textbf{Min}\ \ Z_3 = & \sum_{i=1}^{N} (f_i X_i + 0.75 \times sc \times r \times STOR_i) \\ & + \sum_{i=1}^{N} c(0.25STOR_i + 0.75 \times r \times STOR_i) dp_i + \sum_{i=1}^{N} cM_i dp_i \\ & + \sum_{i=1}^{N} \sum_{j=1}^{N} cXC_j Z_{i,j} ds_{i,j} + \sum_{i=1}^{N} \sum_{j=1}^{N} cXM_j Z_{i,j} ds_{i,j}\end{aligned} \tag{3}$$

The objective (1) maximizes the number of low income farmers to be covered. It is expressed by the percentage of the selected poor farmers to the whole poverty population. Farmers whose income is below a certain poverty level are defined as the poor. The number of farmers is calculated by supply points. Each supply point is associated with 3 types of data: population, average income of the population and the cassava production capacity. The objective (2) maximizes the average income increase rate of the covered poor farmers. The original income of a supply point is obtained by multiplying the average income of a supply point to the population in that supply point. This objective reflects the extent of income increase resulted from the program. The objective (3) minimizes the sum of the fixed warehousing cost, cassava storage cost, cassava and mud transportation cost. The storage cost varies with amount of cassava stored in that processing center. In each processing center, 25% cassava is transported in fresh and the rest is stored and transported to the manufacturing plant in the form of dried flour. The conversation factor r is included in the cost to transfer fresh crops into dried ones. The protein feed transportation cost is not included in the model because of its small quantity. The feed is less than 2% of the total quantities of cassava and mud shipment of 840,000 tons (Administration Office for Guang'xi New and High Technology, 2000). However, as feed transportation is a part of the shipment task in the project and an optimal vehicle routing strategy can save the transportation cost, we discuss feed transportation and vehicle route design later in this thesis.

As stated previously, the cost objective contradicts to the objective of poverty coverage. Contradiction also exists between the first objective and the second objective. Examination from the formulation of the second objective reveals that the improvement of the second objective can be achieved either by enlarging the cassava collection quantity from the supply points or by reducing the number of the supply points. While farmers as many as possible are encouraged to participate in the project under the objective of population coverage, the goal of average income increase rate limits the number of farmers to the fewest such that each farmer can earn the highest income.

Constraints

The cassava collected from the supply points should satisfy the manufacturing plant demand, but the quantity should not be excessive to cause cassava production waste.

$$d \leq \sum_{j=1}^{N} XC_j \leq \bar{\alpha}\ d \tag{4}$$

The cassava collected from a supply point cannot exceed the production capacity of that supply point.

$$XC_j \leq cap_j\ Y_j \qquad \forall j \tag{5}$$

There is a minimum quantity for the manufacturing plant to collect cassava from a supply point. The cassava collected from a supply point should be no less than this quantity. It ensures that the manufacturing plant has minimum profit to earn for cassava collection after excluding the transportation cost and other operation cost associated with collection activity.

$$XC_j \geq col\ Y_j \qquad \forall j \tag{6}$$

The storage quantity of cassava in a warehouse is composed of cassava collecting from its covered supply points. Although cassava is stored in the dried form, the storage quantity refers to those of fresh cassava crops for calculation convenience. They are translated into dried quantity when calculating storage cost.

$$\sum_{j=1}^{N} XC_j Z_{i,j} = STOR_i \qquad \forall i \tag{7}$$

The amount of mud stored in a warehouse is equal to the entire amount distributed to its covered supply points.

$$\sum_{j=1}^{N} XM_j Z_{i,j} = M_i \qquad \forall i \qquad (8)$$

The manufacturing plant distributes mud to the warehouses.

$$\sum_{i=1}^{N} M_i = mprod \qquad (9)$$

The storage in a warehouse is zero if that warehouse is not selected. *BIGNUMBER* is a sufficiently large number.

$$STOR_i \leq BIGNUMBER \times X_i \qquad \forall i \qquad (10)$$

If a supply point is selected, there is a warehouse to serve that supply point.

$$\sum_{i=1}^{N} Z_{i,j} = Y_j \qquad \forall j \qquad (11)$$

Once a warehouse is selected, it serves at least one supply point.

$$\sum_{j=1}^{N} Z_{i,j} \geq X_i \qquad \forall i \qquad (12)$$

If a warehouse is not selected, neither supply point is served by that warehouse.

$$Z_{i,j} \leq X_i \qquad \forall i,j \qquad (13)$$

$Z_{i,j}$, Y_j and X_i are binary numbers.

$$X_i \in (0,1) \qquad Y_j \in (0,1) \qquad Z_{i,j} \in (0,1) \qquad (14)$$

In summary, the complete model for determining and allocating cassava production and processing centers is presented below.

$$\textbf{Max} \quad Z_1 = \frac{\sum_{j=1}^{N} l_j Y_j p_j}{\sum_{j=1}^{N} l_j p_j} \tag{1}$$

$$\textbf{Max} \quad Z_2 = \frac{pro \sum_{j=1}^{N} l_j XC_j}{\sum_{j=1}^{N} l_j Y_j p_j inc_j} \tag{2}$$

$$\textbf{Min} \quad Z_3 = \sum_{i=1}^{N} (f_i X_i + 0.75 \times sc \times r \times STOR_i) \tag{3}$$

$$+ \sum_{i=1}^{N} c(0.25STOR_i + 0.75 \times r \times STOR_i) dp_i + \sum_{i=1}^{N} cM_i dp_i$$

$$+ \sum_{i=1}^{N} \sum_{j=1}^{N} cXC_j Z_{i,j} ds_{i,j} + \sum_{i=1}^{N} \sum_{j=1}^{N} cXM_j Z_{i,j} ds_{i,j}$$

Subject to

$$d \le \sum_{j=1}^{N} XC_j \le \bar{\alpha}\, d \tag{4}$$

$$XC_j \le cap_j\, Y_j \qquad \forall j \tag{5}$$

$$XC_j \ge col\, Y_j \qquad \forall j \tag{6}$$

$$\sum_{j=1}^{N} XC_j Z_{i,j} = STOR_i \qquad \forall i \tag{7}$$

$$\sum_{j=1}^{N} XM_j Z_{i,j} = M_i \qquad \forall i \tag{8}$$

$$\sum_{i=1}^{N} M_i = mprod \tag{9}$$

$$STOR_i \le BIGNUMBER \times X_i \qquad \forall i \tag{10}$$

$$\sum_{i=1}^{N} Z_{i,j} = Y_j \qquad \forall j \tag{11}$$

$$\sum_{j=1}^{N} Z_{i,j} \geq X_i \qquad \forall i \qquad (12)$$

$$Z_{i,j} \leq X_i \qquad \forall i, j \qquad (13)$$

$$X_i \in (0,1) \qquad Y_j \in (0,1) \qquad Z_{i,j} \in (0,1) \qquad (14)$$

The presented model is a traditional location/allocation model but with modifications to fit the needs of the project. It contains the selection process of supply points in addition to the location of facilities and allocation of the supply points to the facilities. Moreover, it not only considers the facility locations, but also determines the amount of cassava to be collected from each supply point. In solving this model, both supply points and warehouses are determined simultaneously. Neither the locations of supply points nor those of warehouses are determined until all three objectives are satisfied. The model utilizes the maximal covering formulation in selecting farmers. Instead of coverage distance, the poverty level is used to limit the supply points to be served. The fixed charge facility location model is used to determine the locations of warehouses. The number and locations of warehouses depend on the trade-off between warehouse fixed costs and transportation cost.

3.2 Transportation Subproblem

Cassava and mud are transported through the network in straight line trips. The average daily cassava demand is around 700 tons in dried and 2,200 tons in fresh when 360 days are estimated for a whole year (Guilin University of Electronic Technology, 2002). With trucks of 8 ton capacity being used, this huge quantity requires several fleets of trucks to travel multiple trips from processing centers to the manufacturing plant to meet the production demand. In their return trips the fleets may carry mud to processing centers to take advantage of truck capacity. The transportation of cassava and mud in the segments between the processing centers and farmers is in line trip as well. There is 780,000 tons of fresh cassava transported to processing centers in three months with average around 8,700 tons in a day (30 days in a month) and 60,000 tons of mud transported to farmers in one and a half month with daily average around 1,300 tons. The way of shipping protein feed from the manufacturing plant to the farmers is different. Protein feed is highly concentrated nutrition feed. Farmers usually mix it with other available feed to enhance feed nutrition value when raising poultry. Protein feed has demand yearly long from farmers but in small amount due to its high price. Normally farmers in a town require no more than 1 ton in a week. Because of the small demand, a truck may travel several towns to distribute feed to enhance delivery efficiency. In the transportation subproblem, we study the protein feed distribution among farmers. We establish the optimal routes departing from the manufacturing plant to cover all towns considered in the area.

3.2.1 Model Formulation

Assumption

- Transportation cost is a linear function of distance traveled by the fleets of trucks.

Notation

$i, j = 0,..,N$ nodes ($i, j = 1$: the manufacturing plant)

k : truck number.

Variables

$$Z_{i,j,k} = \begin{cases} 1 & \text{truck } k \text{ goes directly from } i \text{ to } j, \\ 0 & \text{otherwise.} \end{cases}$$

Parameters

$d_{i,j}$ = shortest distance between node *i* and node *j* (km).

D = maximum distance can be traveled by a truck (km).

$U_{i,k}$, $U_{j,k}$ = any positive integer number.

The Model

Objectives

Minimize the link distance

$$\text{Min} \quad \sum_{i=1}^{N} \sum_{j=1}^{N} \sum_{k=1}^{K} d_{i,j} Z_{i,j,k} \tag{16}$$

Constraints

$$\sum_{i=1}^{N} \sum_{k=1}^{K} Z_{i,j,k} = 1 \qquad j \neq 1 \quad \forall j \tag{17}$$

$$\sum_{i=1}^{N} \sum_{j=1}^{N} d_{i,j} Z_{i,j,k} \leq D \qquad \forall k \tag{18}$$

$$\sum_{i=1}^{N} Z_{i,j,k} = \sum_{i=1}^{N} Z_{j,i,k} \qquad \forall j, k \tag{19}$$

$$U_{i,k} - U_{j,k} + N Z_{i,j,k} \leq N - 1 \qquad i \neq j \quad i \neq 1 \quad j \neq 1 \quad \forall i, j, k \tag{20}$$

$$Z_{i,j,k} = 0 \qquad i = j \quad \forall i, j, k \tag{21}$$

$$\sum_{j=1}^{N} Z_{1,j,k} \leq 1 \qquad \forall k \tag{22}$$

$$Z_{i,j,k} \in (0,1) \tag{23}$$

The objective function (16) minimizes the link cost. Constraint (17) assigns each supply point to a route. Route distance constraint is satisfied in constraint (18). Constraint (19) states that a fleet must leave the node after it enters the node. Constraint (20) eliminates subtours. Constraint (21) ensures a fleet cannot travel inside node. Constraint (22) ensures that each route must be originated from the manufacturing plant.

The model is a standard vehicle routing model. It provides the information about how many routes are required and what is the sequence of the demand points to be visited in a route.

Chapter 4

Model Solutions and Result Analysis

In this chapter, we first present the method to solve the model constructed in chapter 3. We then analyze the results from solving the location model and those from the transportation submodel.

4.1 Solution Method

In solving multiple objective optimization problems, a solution that optimizes all objective functions can rarely be found because of the conflicting natures of the multiple objectives. Trade-off or compromise solutions that improve the value of one of the objectives with less preferred values of other objectives are adopted instead. The benefit of a trade-off solution is that it offers broader decisions for decision makers to select rather than informs the decision makers a single solution. Therefore, finding the trade-off solutions is a focus of multi-objective analysis.

There are many methods reported in the literature to generate compromised solutions for multi-objective integer linear programming problems. The widely used ones are weighting method, constraint method (Cohon, 1978) and goal programming. The weighting method consists of assigning each objective a weight as a coefficient and minimizing or maximizing the weighted sum of objectives. It generates compromised solutions by varying the values of the weights. The effect of this method is twofold. On the one hand, it is straight-forward and easy to implement. On the other hand, time consuming fine-tuning process is required to find satisfactory solutions. It lacks a standard to guide weight selection and weights are determined arbitrarily in some cases. For instance, equal weights are assigned to objectives when these objectives have same importance. However, difficulty may occur on weight setup in case of priority importance or different unit levels among the objectives.

The constraint method optimizes one of the objectives subject to constraints of the values for the other objectives (Jayaraman, 1999). A series of compromised solutions are generated by varying the bounds of the other objectives. It is a relatively simple method. Both the weighting method and the constraint method transfer a multi-objective problem into a single objective problem for optimization.

Goal programming is another alternative method to solve linear multi-objective optimization problems. The basic idea of goal programming is to set up goals for original objectives and to minimize deviation from those goals. The detailed definition and solution procedure can be found in Hillier and Lieberman (2002). Due to its characteristic of simultaneous minimization of several deviations, goal programming is an efficient tool for solving multi-objective problems with more than two objectives. Goal programming removes tiresome weighting processes but requires specific targeted goals from decision makers. It is more likely to give a definite solution rather than a series of compromised solutions, although different goals can obtain different compromised solutions.

In this research, the constrained method is applied to solve our problem. It eliminates the demerit of uncertain weights and reduces the problem size by solving the model step by step. Besides, it is easy to implement and the result matches our aim to present various solutions rather than a single solution to assist decision making.

We set the objective priority in sequence of the Maximum Poverty Population Coverage, the Highest Average Income Increase Rate, and the Minimum Total Cost in order to apply the constrained method. We solve the model sequentially according to the objective priorities.

The detailed procedure is provided below.

1) Maximize submodel $Z_1 = \frac{\sum_{j=1}^{N} l_j Y_j p_j}{\sum_{j=1}^{N} l_j p_j}$, subject to constrains (4)-(6), find Z_1;

2) Maximize submodel $Z_2 = \frac{pro \sum_{j=1}^{N} l_j XC_j}{\sum_{j=1}^{N} l_j Y_j p_j inc_j}$, subject to constrains (4)-(6) and

$\frac{\sum_{j=1}^{N} l_j Y_j p_j}{\sum_{j=1}^{N} l_j p_j} = Z_1$, calculate Z_2;

3) Minimize submodel

$$Z_3 = \sum_{i=1}^{N} (f_i X_i + 0.75 \times sc \times r \times STOR_i) + \sum_{i=1}^{N} c(0.25STOR_i + 0.75 \times r \times STOR_i)dp_i + \sum_{i=1}^{N} cM_i dp_i + \sum_{i=1}^{N} \sum_{j=1}^{N} cXC_j Z_{i,j} ds_{i,j} + \sum_{i=1}^{N} \sum_{j=1}^{N} cXM_j Z_{i,j} ds_{i,j}$$

subject to constrains (4)-(14), $\frac{\sum_{j=1}^{N} l_j Y_j p_j}{\sum_{j=1}^{N} l_j p_j} = Z_1$, and $\frac{pro \sum_{j=1}^{N} l_j XC_j}{\sum_{j=1}^{N} l_j Y_j p_j inc_j} = Z_2$, find Z_3.

The objective Z_2 and part of objective Z_3 is not strictly linear formulation. We transform the non-linear terms to linear terms as shown in the Appendixes. The solutions of the above single objective integer programming models are obtained by using LINGO 8.0. Solving submodel 3 requires extensive computation due to large number of integer variables in the model caused by relative large number of nodes in the network. To improve computational efficiency, we developed a heuristic procedure to solve this submodel as discussed below.

4.2 A Heuristic Method for solving Submodel 3

Submodel 3 mentioned above is difficult to solve due to the large number of candidate nodes. In this section, we introduce a heuristic method to solve this problem. The basic idea is to reduce the number of candidate nodes by excluding some nodes in the network. The exclusion is done by solving the same minimization problem with a simplified distance objective function. The distance objective is proportional to both distance traveled and shipment quantity. Smaller number of nodes is selected from the large number of candidate nodes by solving this simplified model.

These selected nodes in a smaller scope are used as input to the next detailed cost model. The use of the simplified model can greatly decrease the number of nodes. However, the corresponding cost value of the detail cost objective is only an approximation. It is possible that some nodes which should be selected are excluded by the simplified model. In the simplified model, we only consider the distance effect on decreasing the transportation cost and neglect the warehouses' contribution. When the raw material is transported through a warehouse (processing center), the dehydration process significantly reduces the material and hence the transportation cost from the warehouse to the plant. The savings of transportation cost for a supply point *j* can be calculated as

$$S = c \times XC_j \times D_3 - (c \times XC_j \times D_1 + 0.75 \times c \times r \times XC_j \times D_2 + 0.25 \times c \times XC_j \times D_2),$$

where D_1 is the distance between the supply point and the warehouse, D_2 is the distance between the warehouse and the plant, and D_3 is the distance between the supply point and the plant. The warehouse contributes to the reduction of the transportation cost when the value of S is positive. Some of the supply point excluded by the simplified model should be included considering the warehouse contribution to the transportation cost.

In order to achieve better results, we may select more nodes as supply points. The selection is performed by applying the simplified model to the nodes currently not selected. The cassava demand from these nodes is limited to a percentage of θ of the total demand. More nodes are selected with larger value of θ. With each selection, we apply the detailed cost objective model. The results are compared to observe if the costs are reduced. The procedure terminates when cost reduction is less than a given ε, where ε is a positive number. The heuristic procedure is described below in detail.

1) Minimize $Z_3 = \sum_{j=1}^{N} XC_j Y_j dm_j$, subject to constrains (4)-(6), $\frac{\sum_{j=1}^{N} l_j Y_j p_j}{\sum_{j=1}^{N} l_j p_j} = Z_1$, and $\frac{pro \sum_{j=1}^{N} l_j XC_j}{\sum_{j=1}^{N} l_j Y_j p_j inc_j} = Z_2$. dm_j is the distances from the manufacturing plant to individual supply points j. Identify the supply point j, $j \in \{1,..,N; Y_j = 1\}$.

2) Set the supply points j from 1) as candidate supply points; assume $\sum_{j=1}^{N} Y_j = K$, minimize

$$Z_4 = \sum_{i=1}^{K} (f_i X_i + 0.75 \times sc \times r \times STOR_i)$$
$$+ \sum_{i=1}^{K} c(0.25STOR_i + 0.75 \times r \times STOR_i)dp_i + \sum_{i=1}^{K} cM_i dp_i$$
$$+ \sum_{i=1}^{K} \sum_{j=1}^{K} cXC_j Z_{i,j} ds_{i,j} + \sum_{i=1}^{K} \sum_{j=1}^{K} cXM_j Z_{i,j} ds_{i,j},$$

subject to constrains (4)-(14), $\dfrac{\sum_{j=1}^{K} l_j Y_j p_j}{\sum_{j=1}^{K} l_j p_j} = Z_1$, and $\dfrac{pro \sum_{j=1}^{K} l_j XC_j}{\sum_{j=1}^{K} l_j Y_j p_j inc_j} = Z_2$.

Identify warehouse i, $i \in \{1,..,K; X_i = 1\}$.

3) Assume $N - K = L$ minimize $Z_3 = \sum_{j=1}^{L} XC_j Y_j dm_j$, subject to constrains (4)-(6). The constraint (4) changes to $\theta_1 d \le \sum_{j=1}^{L} XC_j \le \theta_1 \bar{\alpha}\ d$. Identify the supply points j, $j \in \{1,..,L; Y_j = 1\}$.

4) Set the points j from the results of 1) and 3) as candidate supply points, the points i from the results of 2) and 3) as candidate warehouses. Set M as the sum of points i and j.

Minimize $Z_4 = \sum_{i=1}^{M} (f_i X_i + 0.75 \times sc \times r \times STOR_i)$

$$+ \sum_{i=1}^{M} c(0.25STOR_i + 0.75 \times r \times STOR_i)dp_i + \sum_{i=1}^{K} cM_i dp_i$$

$$+ \sum_{i=1}^{M} \sum_{j=1}^{M} cXC_j Z_{i,j} ds_{i,j} + \sum_{i=1}^{M} \sum_{j=1}^{M} cXM_j Z_{i,j} ds_{i,j},$$

subject to constrains (4)-(14), $\dfrac{\sum_{j=1}^{M} l_j Y_j p_j}{\sum_{j=1}^{M} l_j p_j} = Z_1$, and $\dfrac{pro \sum_{j=1}^{M} l_j XC_j}{\sum_{j=1}^{M} l_j Y_j p_j inc_j} = Z_2$, determine the supply points j and warehouses i.

5) Repeat step 3), 4) to calculate Z_4 with $\theta_1, \theta_2 \dots$ until θ of the total demand, if necessary. Stop when cost reduction is equal to or less than ε.

The heuristic is illustrated by a flow chart in Figure 4-1. In our problem, we increase θ from 10% to 20%, 30%... until reduction on cost is equal to or less than 1.5%. This heuristic is implemented by LINGO linked with the Excel data sheet. Excel was used as a data intermediary to receive and sort data from LINGO output and input to the next step of LINGO computation. This heuristic is easy to implement. The solutions at each iteration can be obtained with about 30 minutes of computation on a PC-computer with AMD Duron 12.9 GHz processor and 224 MB of RAM. The LINGO codes of the model are attached in the Appendixes.

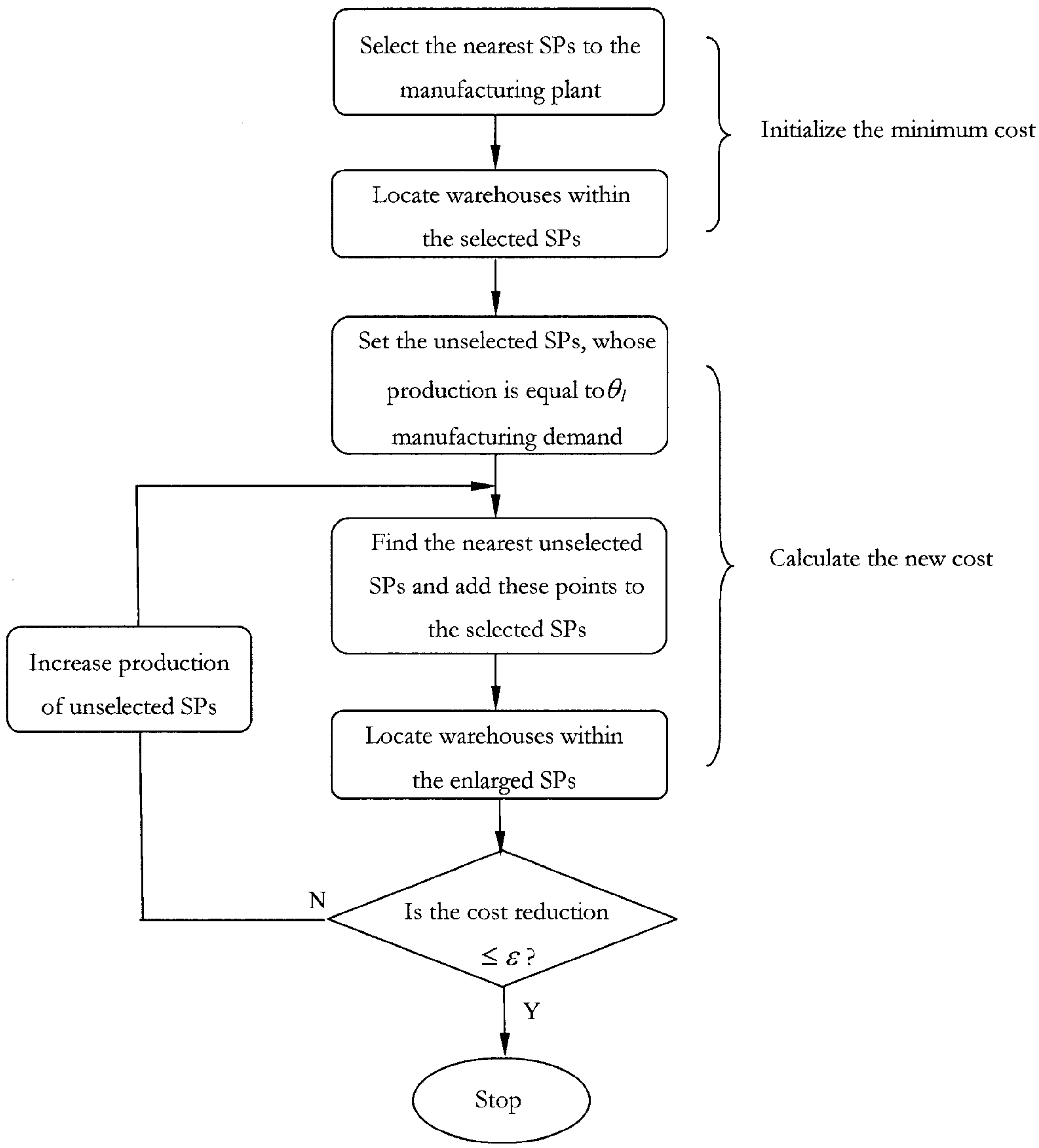


Figure 4-1 Flow Chart of the Heuristic Method (SP: supply point).

4.3 Data for the studied problem

We solved the problem based on yearly production. A total of 780,000 tons of fresh cassava in each year is required to satisfy the 100,000 ton ethanol production (Guilin University of Electronic Technology, 2002). The manufacturing plant with such capacity can produce 60,000 ton mud. In our problem, we assume that the quantity of mud shipped to the farmers is proportional to that of cassava collected from the farmers. Farmers who plant more cassava receive larger quantity of mud. Cassava is a fundamental crop in Chongzuo and Chongzuo has one of the largest cassava production fields in Guang'xi province. It consists of six administrative districts covering about 70 towns with each town producing large amounts of cassava crops. There are 3 sets of data associated with each town: income, population and cassava production capacity. The income of towns and population data can be found from the websites of local governments (Websites of local governments in Guang'xi, China, 2003). The population of each town is estimated due to uncompleted government data. The cassava production capacity is estimated but based on the quantity of maximum arable land. The obtained and estimated data for each town considered in the problem are given in Table 4-1. The distance between the potential processing centers and individual supply points, which is the distance among towns, is calculated by applying local maps to Visio (Microsoft Visio Ver.6.0).

We use 2,000 Yuan (400 CAD) as the poverty level in solving the problem. It is slightly higher than the average net annual peasant income of 1,875 Yuan in Guang'xi in 1997 (Guang'xi People's government, 2003) and differs from the government published poverty line of 625 Yuan. Under such poverty level, 33 towns are categorized as poor towns. We estimated that the annual operating cost of a processing center is 59,000 Yuan. The same operating cost is used for all potential sites of processing centers as they distribute in the same district of the province. The storage cost of cassava is defined as 1 Yuan per ton. The standard shipping cost in local area is 0.3 Yuan per kilometer per ton. The average revenue from selling cassava is 180 Yuan per ton. As a total of 260,000 tons of cassava flour can be extracted from 780,000 tons of fresh cassava, the yield rate is 0.3333 (Guilin University of Electronic Technology, 2002). In our problem, we allow a 5% over supply on top of the total required 780,000 tons. In addition, if a town is covered as a supply point, it will provide a minimum of 1,000 tons of cassava. The complete data sets are presented in the Appendixes.

Table 4-1 Population, Income and Production Capacity of Towns

Administrative district		Town	Population	Average Income (Yuan)	Production Capacity (ton)
Tiandeng	1	Jinjie	39,462	2,535	4,521
	2	Jinyuan	12,331	3,019	6,752.2
	3	Tuokan	36,621	2,418	4,551.8
	4	Tiandeng	7,000	3,758	10,519
	5	Dongkang	29,082	3,025	4,906.2
	6	Ninggan	19,859	3,200	5,239
	7	Longming	23,069	3,430	4,992
	8	Fuxin	32,040	2,300	1,192.2
	9	Shangying	34,843	2,500	3,372.2
	10	Jindong	12,567	1,441.8	2,311.4
Daxin	11	Fulong	15,209	1,480.5	34,927
	12	Wushan	10,081	1,589.7	32,654
	13	Changming	15,529	1,492	14,358.2
	14	Longmen	8,470	2,151.3	23,312.6
	15	Quanming	13,484	2,084.4	32,193.2
	16	Taocheng	39,000	2,271.6	46,410
	17	Lanyu	31,533	2,291	37,305
	18	Naling	16,081	2,151	49,953
	19	Encheng	15,146	2,170.6	19,118
	20	Leiping	35,082	2,298	52,230
	21	Kanyu	17,277	2,187	9,668.6
	22	Bayou	17,872	2,010.2	24,378.2
	23	Shoulong	14,554	1,272	12,126.4
	24	Xialei	14,000	1,931.4	17,937.2
	25	Tuhu	10,744	1,796	8,110.6

Table 4-1 Population, Income and Production Capacity of Towns (continued)

Administrative district		Town	Population	Average Income (Yuan)	Production Capacity (ton)
Longzhou	26	Jinlong	11,250	1,375	15,360.2
	27	Zhoupu	18,700	1,500	14,261
	28	Xiangshui	14,096	2,216	27,456
	29	Wude	18,572	1,665	6,828.6
	30	Shanglong	17,300	1,245	10,200
	31	Shangjin	14,400	1,829	21,507
	32	Shuikou	18,691	1,731	24,517.6
	33	Xiadong	20,649	1,560	11,718.8
	34	Longzhou	15,708	1,971	9,083.8
	35	Binqiao	8,800	1,481	22,128
	36	Bajiao	11,369	1,277	18,903
	37	Shangxiang	12,790	1,839	7,155.2
Ningming	38	Tingliang	11,449	2,011.6	10,755.4
	39	Tuolong	12,228	1,748	11,141.3
	40	Chengzhong	20,250	1,554	17,152.1
	41	Zhaian	13,749	1,943	30,128.2
	42	Mingjiang	9,775	1,857	13,040
	43	Dongan	22,813	2,036	17,265.6
	44	Bangun	16,230	1,635	10,681.6
	45	Haiyuan	19,855	1,780	31,028.4
	46	Nakan	11,864	1,679	12,734.8
	47	Nanan	14,023	1,533	16,173.6
	48	Tongmian	12,333	1,727	4,346
	49	Yulang	10,270	1,328	11,063.1
	50	Aidian	9,980	2,866	7,295.6
Chongzuo	51	Xinhe	15,377	2,375	83,040
	52	Zuozhou	18,000	2,339	33,529.6
	53	Nalong	22,241	1,136	27,851.6
	54	Toulu	14,235	2,262	23,812
	55	Laituan	17,731	2,176	22,148.2
	56	Taiping	14,423	2,062	29,974.6
	57	Jiangzhou	20,000	2,432	15,316.6
	58	Luobai	23,874	2,295	20,334.6
	59	Banli	13,117	1,312	19,008.6
Fusui	60	Qujiu	17,849	2,438	4,754.6
	61	Liuqiao	30,379	2,128	18,163.6
	62	Dongluo	22,047	2,000	10,589
	63	Dongmen	21,671	1,943	17,360.4
	64	Quli	49,152	2,080	19,517.8
	65	Yipen	19,231	2,515	16,679
	66	Shanyu	26,064	2,500	13,666.1
	67	Zhongdong	28,534	2,295	10,256.5
	68	Changping	24,547	2,100	15,958.8
	69	Longtou	27,413	1,630	26,470.8
	70	Xinning	9,638	2,562	21,065.2

4.4 Solution analysis

4.4.1 Processing Center Locations

The purpose of the model is to determine the number and locations of both processing centers and farmers under three conflict objectives. A decision to maximize the poverty population coverage is in conflict with a decision to minimize the cost. On the one hand, as many nodes as possible are covered under the maximum population poverty coverage in order to increase the covered population. On the other hand, the objective of the minimum cost forces a smallest number of nodes necessary for the production need to be selected. The same contradiction happens between the two objectives of the maximum poverty population coverage and the maximum average income increase rate of the poor. The value of income increase rate is decreased for every new town added into the selection. Higher income increase rate is achieved with smaller population coverage. The model is solved repeatedly to find the trade-offs among these three objectives. The results are shown in Table 4-2.

As can be seen from Table 4-2, the system cost reaches the maximum when poverty population has full coverage and income increase rate rises to the highest level at such coverage. All of the 33 low income towns are covered at this time. The highest average income increase rate is 11.9% at the full coverage and the maximum system cost is 9,773,244 Yuan. The last solution in the table (solution 15) has the minimum system cost of 7,289,789 Yuan. In the condition of the minimum cost, 25.6% farmers in poverty among the total poor farmers are covered in the program and their average income would be increased by 18.1%. We note that this income increase rate is gained at the minimum cost level, not the highest rate at the coverage of 25.6%.

Table 4-2 Trade-off Solutions

	Poverty Coverage	Average Income Increase Rate	Cost		Number of Supply Points	Number of Processing Centers
			Yuan	CAD		
1	1	11.9%	9,773,244	1,954,649	39	25
2	93.9%	12.4%	9,642,217	1,928,443	37	25
3	89.5%	12.9%	9,597,798	1,919,560	37	25
4	84.6%	13.4%	9,465,491	1,893,098	34	26
5	79.9%	13.9%	9,336,538	1,867,308	34	25
6	74.9%	14.3%	9,246,415	1,849,283	33	25
7	69.8%	14.9%	9,030,442	1,806,088	32	24
8	65.0%	15.5%	8,911,750	1,782,350	31	22
9	59.8%	16.0%	8,770,963	1,754,193	30	23
10	54.9%	16.6%	8,696,554	1,739,311	30	24
11	49.5%	17.1%	8,472,664	1,694,533	30	22
12	44.8%	17.9%	8,149,579	1,629,916	28	22
13	39.9%	18.7%	7,945,284	1,589,057	29	21
14	35.0%	19.6%	7,927,247	1,585,449	29	20
15	25.6%	18.1%	7,289,789	1,457,958	31	18

Figure 4-2 illustrates the relationship among the three competing objectives. The curves in the figure represent different poverty coverage and they increase from left to right. The income increase rate with corresponding cost at each poverty coverage percentage can be observed. The top point of each curve corresponds to the highest average income increase rate and the minimum cost at such income increase rate under specified coverage. The bottom points are the minimum costs at the different poverty coverage levels. The results in Table 4-2 only contain data of the bottom point of the first left curve and those of the top points of all the other curves. The detailed solutions of all points are presented in the Appendixes. Since the model is a discrete facility location model, only the results at separate poverty coverage levels are plotted. In fact, the poverty coverage can be any value between the first and last curve and the solutions cover the whole area with these two curves as borders.

We observe from the chart that the average income increase rate decreases as the poverty population coverage increases. The increase of the income increase rates ranges from 4.4% to 20.6%. The highest average income increase rate of 20.6% is reached at 25.6% poverty coverage. When the poverty coverage increases up to 59.8%, the average income increase rate can only reach to 16%. As the coverage further increases to 100%, the average income increase rate reduces to the lowest value of 11.9%. Such a descending trend is clearly displayed in the upper part of the curves in Figure 4-3. The income increase rates at the minimum cost of the specified coverage also follow a similar trend and are shown in the lower part of the curves. A minimum of 4.4% is achieved at the minimum cost at 100% coverage.

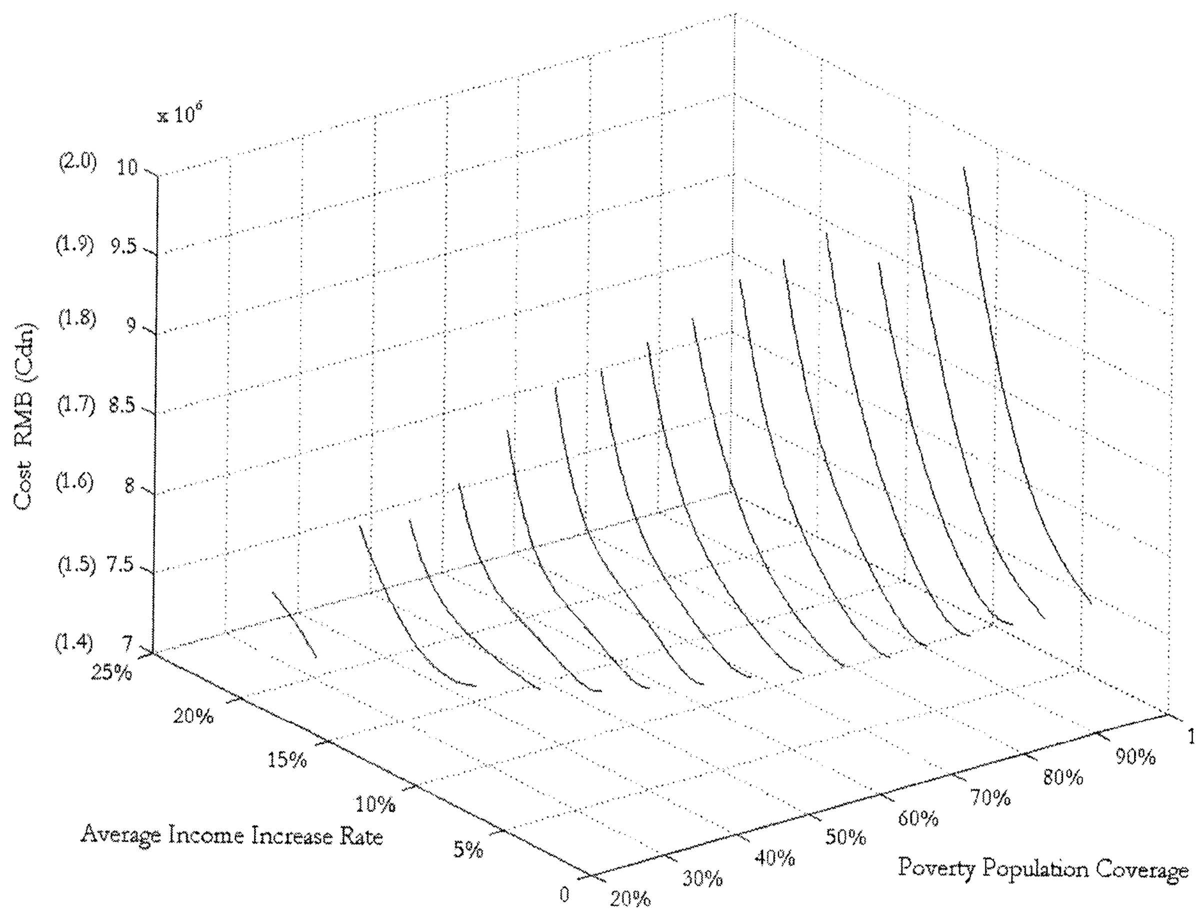


Figure 4-2 The Relationship of three Objectives

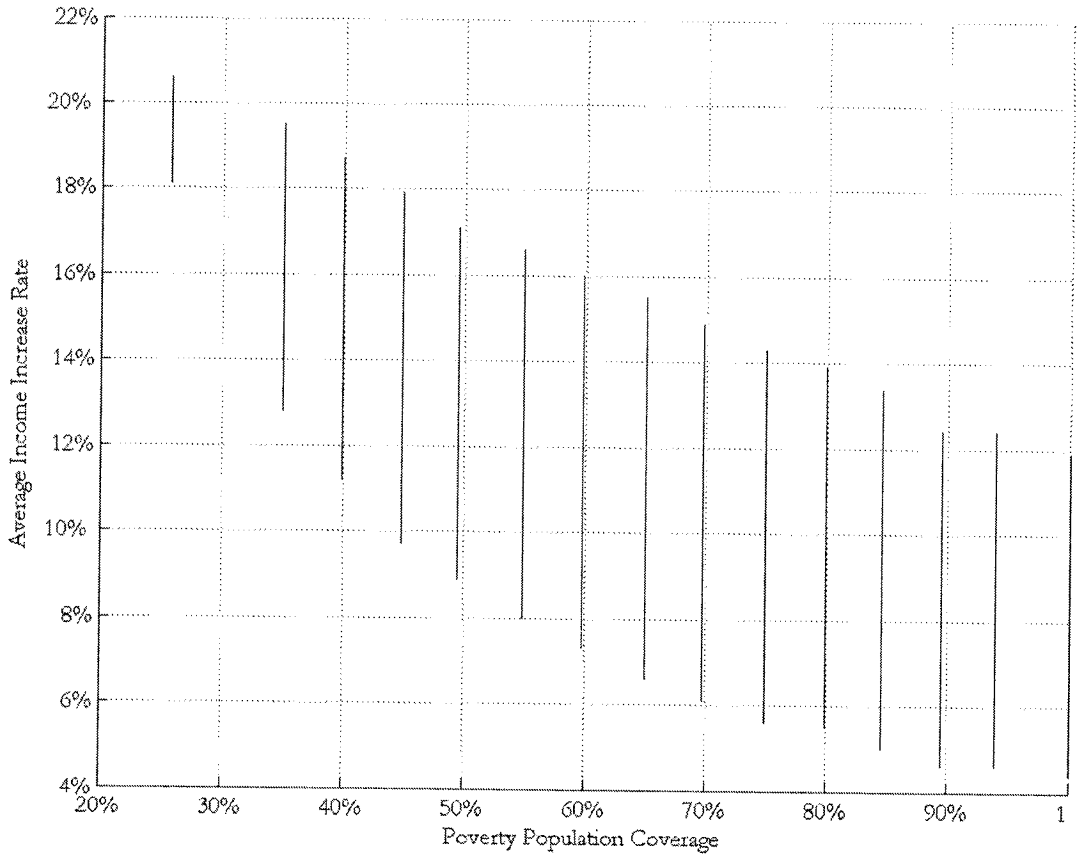


Figure 4-3 Poverty Population Coverage vs. Average Income Increase Rate

Similarly, the trade-off relationship between the poverty coverage and the system cost is shown in Figure 4-4 with only these two objectives. The cost decreases with the reduction of the poverty coverage.

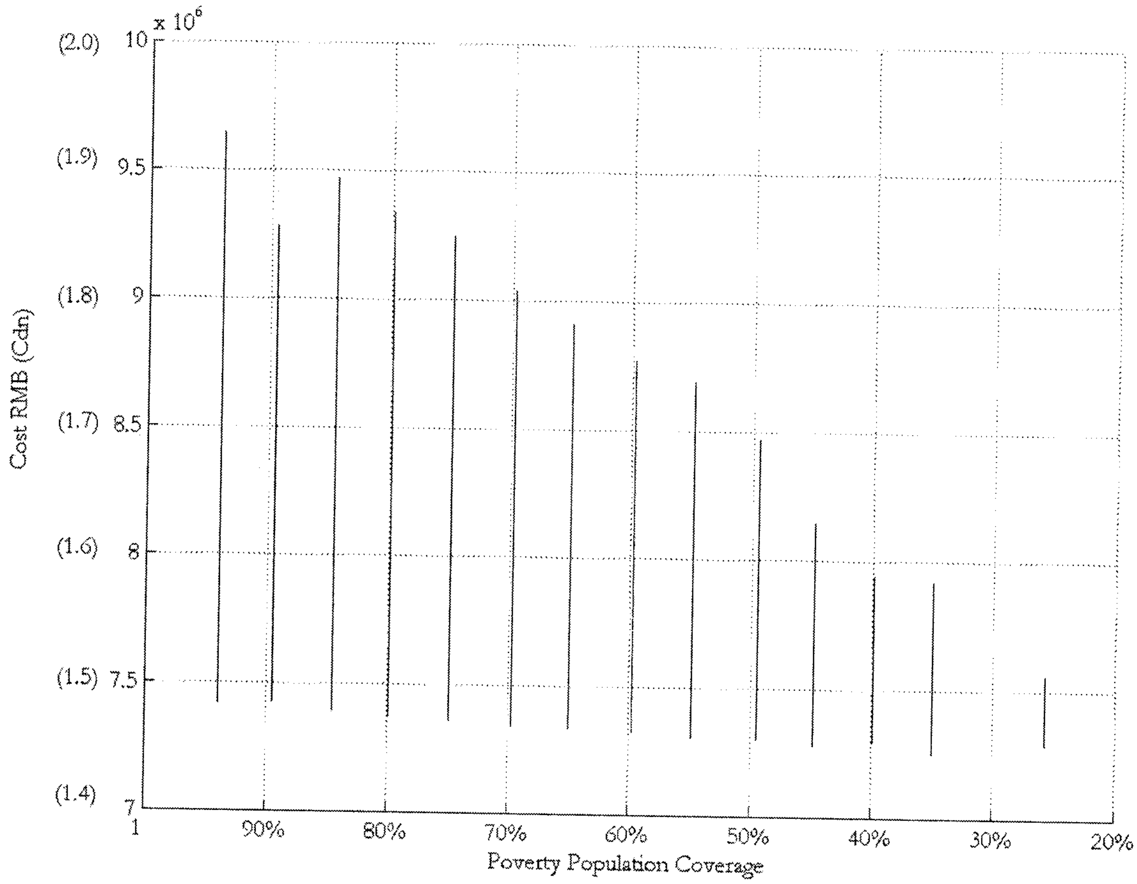


Figure 4-4 Poverty Population Coverage vs. Cost

Figure 4-5 shows the relationship of the average income increase rate and the system cost. Each curve in this figure represents a different poverty coverage level. The poverty coverage decreases from left to right. The curves show that cost increases as income increase rate increases. For the same coverage, higher income increase rate leads to larger cassava collections from low income supply nodes. Such a tendency can be observed from solutions in the Appendixes, where the collection quantities from the poor are marked as the percentage of the total collections. In the studied area, most of the lower income towns are far away from the location where the manufacturing plant will be sited. The average distance of these towns to the manufacturing plant is 77.5 kilometers, which is approximately 7 kilometers more than the average distance from all supply points to the plant. The large cassava collection quantities from the farmers in these towns result in an increase of income increase rate and higher transportation cost.

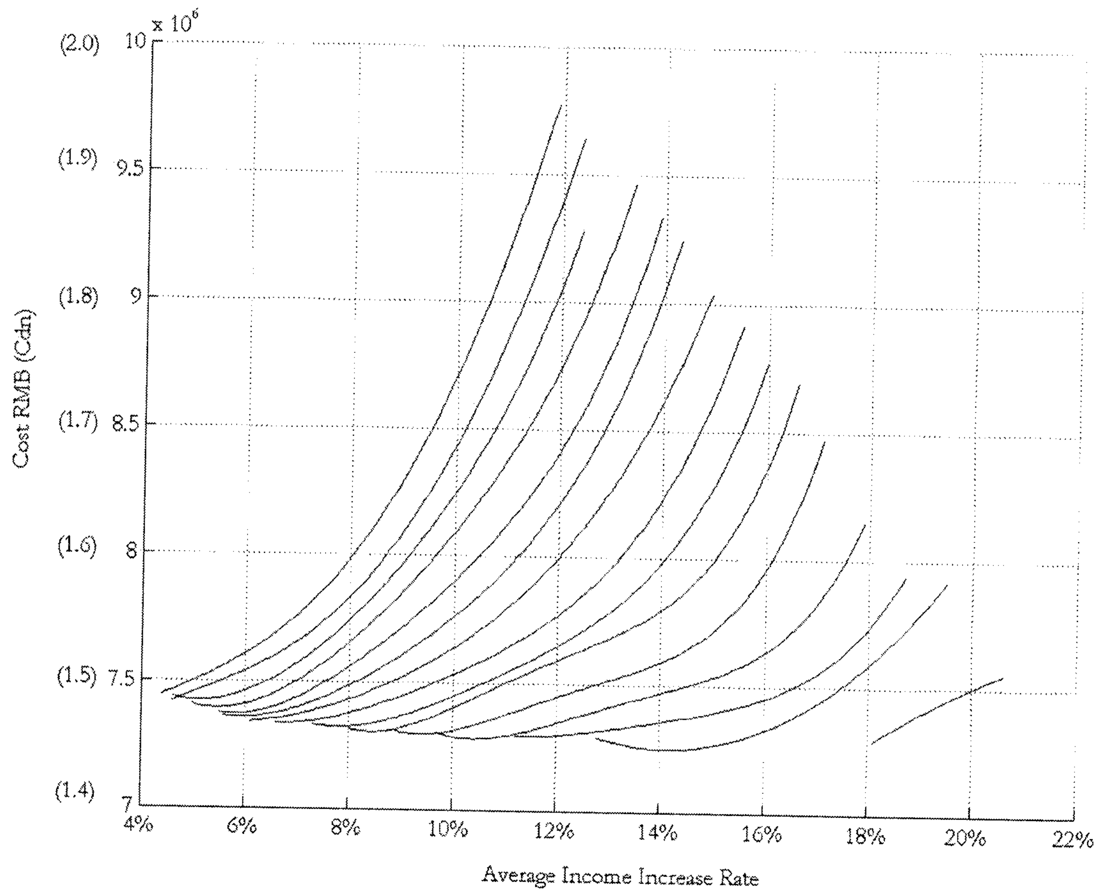


Figure 4-5 Average Income Increase Rate vs. Cost

Figure 4-6 shows the locations of farmers and processing centers with full poverty coverage and the highest income increase rate at such coverage. In this and following figures in this section, the node numbers indicate the towns in the distribution network. When all of the poor farmers are covered to supply cassava to the manufacturing plant, their average income can be increased by 11.9%. Farmers in the 33 poor towns are covered by 25 processing centers. The minimum cost at such poverty coverage and the highest income increase rate is 9,773,244 Yuan. We let the routes in remote towns pass through the towns close to the center in the area before the routes arrive at the center. For example, shipments from town 35 travel through towns 34 and 28 to the manufacturing plant. In Figure 4-6, some towns ship cassava to the nearby processing centers for dehydration process and others build their own processing centers. For example, the processing center located in town 31 serves both town 31 and town 34. The processing center in town 35 only serves town 35 itself. Since the total cassava quantity from poor farmers cannot satisfy the manufacturing plant demand, farmers with higher income in the six closest towns to the manufacturing plant fill the rest of the demand. They are towns 17, 19, 20, 28, 51 and 56. The manufacturing plant is located at town 51. Table 4-3 lists the supply node numbers shown in Figure 4-6 and cassava collection quantity from these nodes. The nodes with processing centers are in boldface.

When the cassava supply system is run with the minimum annual cost of 7,289,789 Yuan, only 25.6% of poor farmers are covered. Their average income increase is 18.1%. 18 processing centers should be established to serve the farmers in 31 towns, 9 of them are poor towns. These 31 towns are closest to the manufacturing plant. A map of the solution is plotted in Figure 4-7.

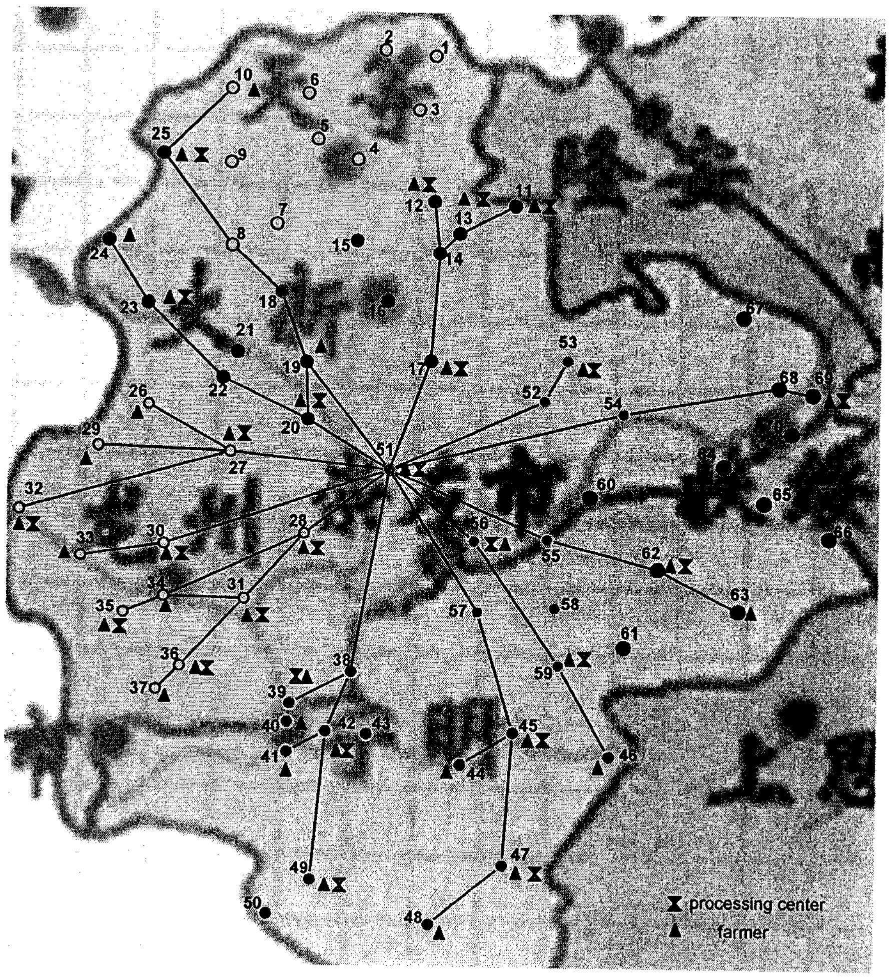


Figure 4-6 Solution at 100% Poverty Coverage, 11.9% Income Increase Rate

Table 4-3 Solution at 100% Poverty Coverage, 11.9% Income Increase Rate

	Cassava Quantity(ton)		Cassava Quantity(ton)		Cassava Quantity(ton)
10	2311.4	29	6828.6	44	10681.6
11	34927	**30**	10200	**45**	31028.4
12	32654	**31**	21507	46	12734.8
13	14358.2	**32**	24517.6	**47**	16173.6
17	37305	33	11718.8	48	4345.8
19	7137.1	34	9083.8	**49**	11063.1
20	52230	**35**	22128	**51**	83040
23	12126.4	**36**	18903	**53**	27851.6
24	17937.2	37	7155.2	**56**	29974.6
25	8110.6	**39**	11141.2	**59**	19008.6
26	15360.2	40	17152.1	**62**	10589.2
27	14261	41	30128.2	63	17360.4
28	27456	**42**	13040	**69**	26470.8

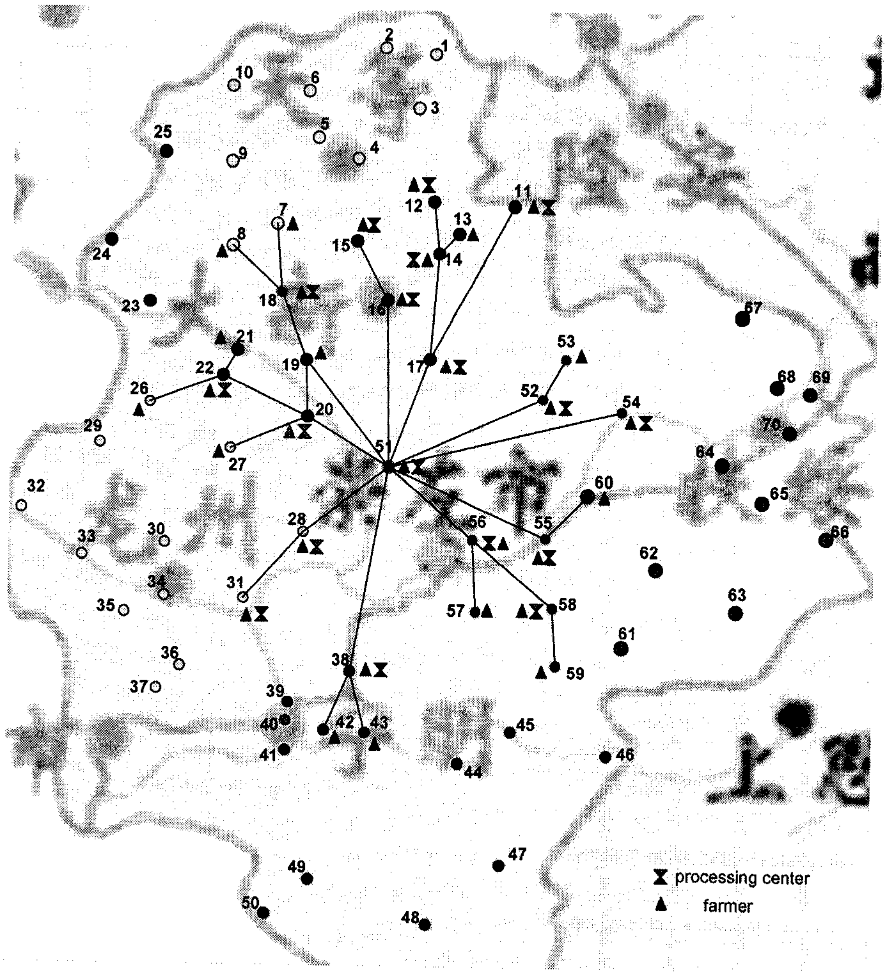


Figure 4-7 Solution at 25.6% Poverty Coverage, 18.1% Income Increase Rate

Table 4-4 Solution at 25.6% Poverty Coverage, 18.1% Income Increase Rate

	Cassava Quantity(ton)		Cassava Quantity(ton)		Cassava Quantity(ton)
7	2884.3	**20**	52230.0	**51**	83040.0
8	1192.2	21	9668.6	**52**	33529.6
11	34927.0	**22**	24378.2	53	27851.6
12	32654.0	26	15360.2	**54**	23812.0
13	14358.2	27	14261.0	**55**	22148.2
14	23312.6	**28**	27456.0	**56**	29974.6
15	32193.2	**31**	21507.0	57	15316.6
16	46410.0	**38**	10755.4	**58**	20334.6
17	37305.0	42	13040.0	59	19008.6
18	49953.0	43	17265.6	60	4754.6
19	19118.0				

When the poverty coverage falls, we observe that the supply points move toward the manufacturing plant and the circle formed by those points becomes smaller. Figure 4-8 and Figure 4-9 are the location maps of the towns with coverage of 74.9% and 44.8%, respectively. When the poverty coverage is reduced, fewer poverty towns are covered. The low income farmers in towns 10, 29, 30, 34, 37, 44, 48 and 62 in Fig. 4-6 are removed from cassava supply as shown in Fig. 4-8. The towns with higher income are then added as supply points or supply more cassava. These towns are selected according to their distances to the manufacturing plant. In Fig. 4-8, towns 16 and 57 are selected among higher income towns as supply points for their closeness to the manufacturing plant and town 19 collects more cassava to satisfy the demand. The new processing centers are then set up in the towns after balancing the fixed cost and transportation cost. For example, the processing center 16 in Fig. 4-8 replaces the processing center 30 in Fig.4-6. When the coverage is further reduced, the poor towns in the right side and upper left part of the map in Fig.4-8 are all removed from supplying cassava shown in Fig. 4-9. They are towns 23, 24, 25, 27, 33, 63 and 69. Some towns close to the manufacturing plant including towns 18, 22 and 55 are added and one town, 57, increases its cassava production volume. The number of poverty nodes continues reducing and that of higher income nodes continues increasing with the decreased poverty coverage until all of farmers are sited in the locations circling around the manufacturing plant in Fig.4-7.

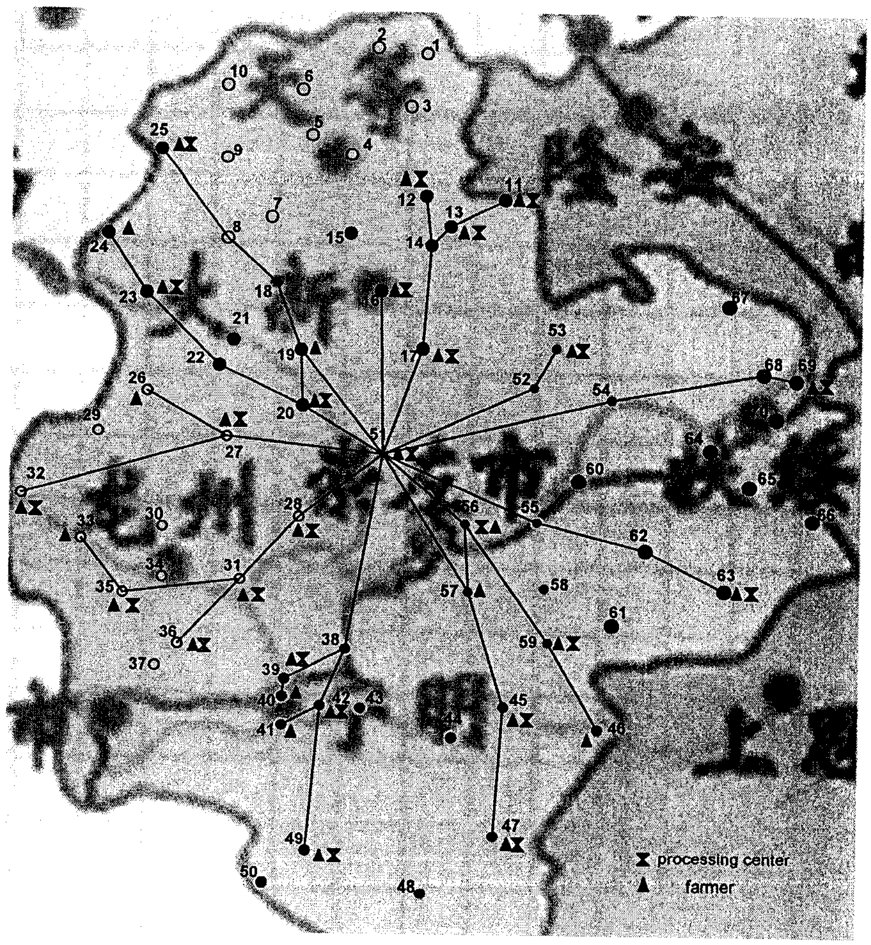


Figure 4-8 Solution at 74.9% Poverty Coverage, 14.3% Income Increase Rate

Table 4-5 Solution at 74.9% Poverty Coverage, 14.3% Income Increase Rate

	Cassava Quantity(ton)		Cassava Quantity(ton)		Cassava Quantity(ton)
11	34927	27	14261	45	31028.4
12	32654	28	27456	46	12734.6
13	14358.2	31	21507	47	16173.6
16	46410	32	24517.6	49	11063.1
17	37305	33	11718.8	51	83040
19	19118	35	22128	53	27851.6
20	52230	36	18903	56	29974.6
23	12126.4	39	11141.2	57	2804.7
24	17937.2	40	17152.1	59	19008.6
25	8110.6	41	30128.2	63	17360.4
26	15360.2	42	13040	69	26470.8

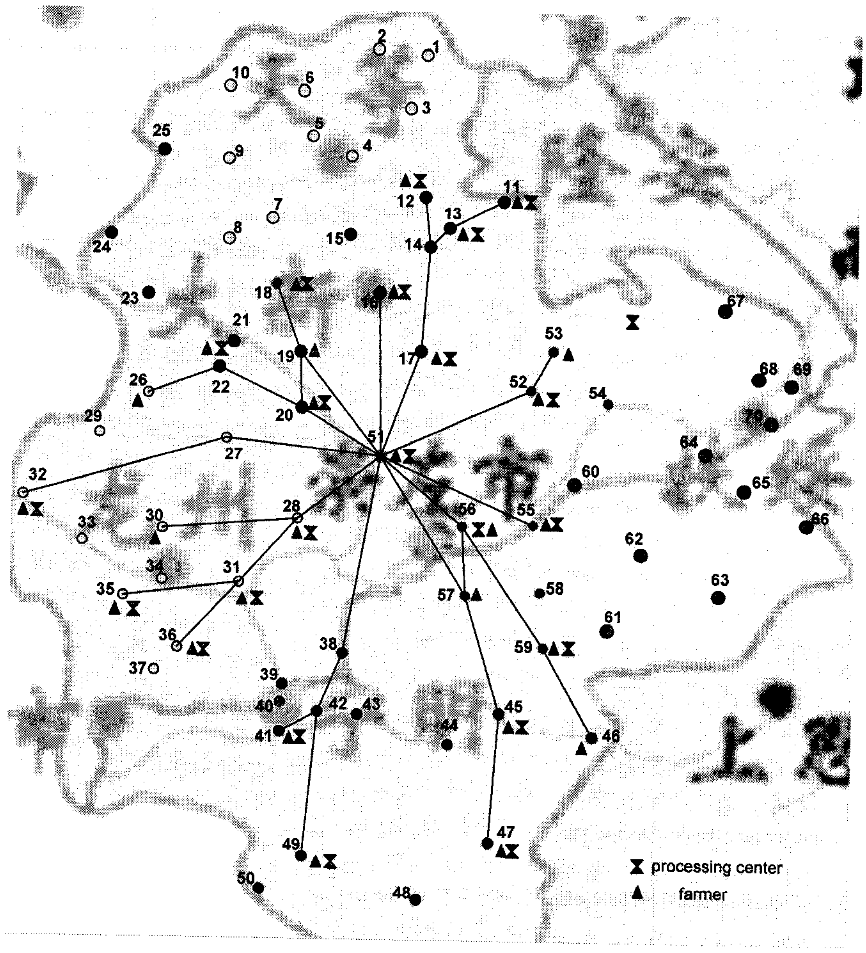


Figure 4-9 Solution at 44.8% Poverty Coverage, 17.9% Income Increase Rate

Table 4-6 Solution at 44.8% Poverty Coverage, 17.9% Income Increase Rate

	Cassava Quantity(ton)		Cassava Quantity(ton)		Cassava Quantity(ton)
11	34927	**28**	27456	**47**	16173.6
12	32654	30	10200	**49**	11063.1
13	14358.2	**31**	21507	**51**	83040
16	46410	**32**	24517.6	**52**	33529.6
17	37305	**35**	22128	53	27851.6
18	49953	**36**	18903	**55**	22148.2
19	19118	**41**	30128.2	**56**	29974.6
20	52230	**45**	31028.4	57	11914.4
22	24378.2	46	12734.3	**59**	19008.6
26	15360.2				

The change of the income increase rate will also affect locations of the processing centers. Figure 4-10 shows locations of the processing centers with 100% poverty coverage and minimum system cost at such coverage. The income increase rate is 4.4% under these two conditions. The poverty coverage level is the same for the solutions shown in Fig. 4-6 and Fig.4-10. The quantities of cassava supplied by poor farmers are reduced from 70% to 26% of the total supply quantities from Fig. 4-6 to Fig. 4-10 due to the decrease of the income increase rate. One can see from Table 4-7, many poor farmers have cassava collections of 1,000 tons, the minimum quantity, when the income increase rate is 4.4%. A high fixed cost of processing center prohibits the towns with reduced quantities, such as towns 11, 23, 25, 30, 32, 35, 39 and 49, continuing as processing centers in Figure 4-10 and those towns combined with other supply points as a group to be covered. Figure 4-10 shows relatively centralized processing center locations around the manufacturing plant compared to those shown in Fig.4-6.

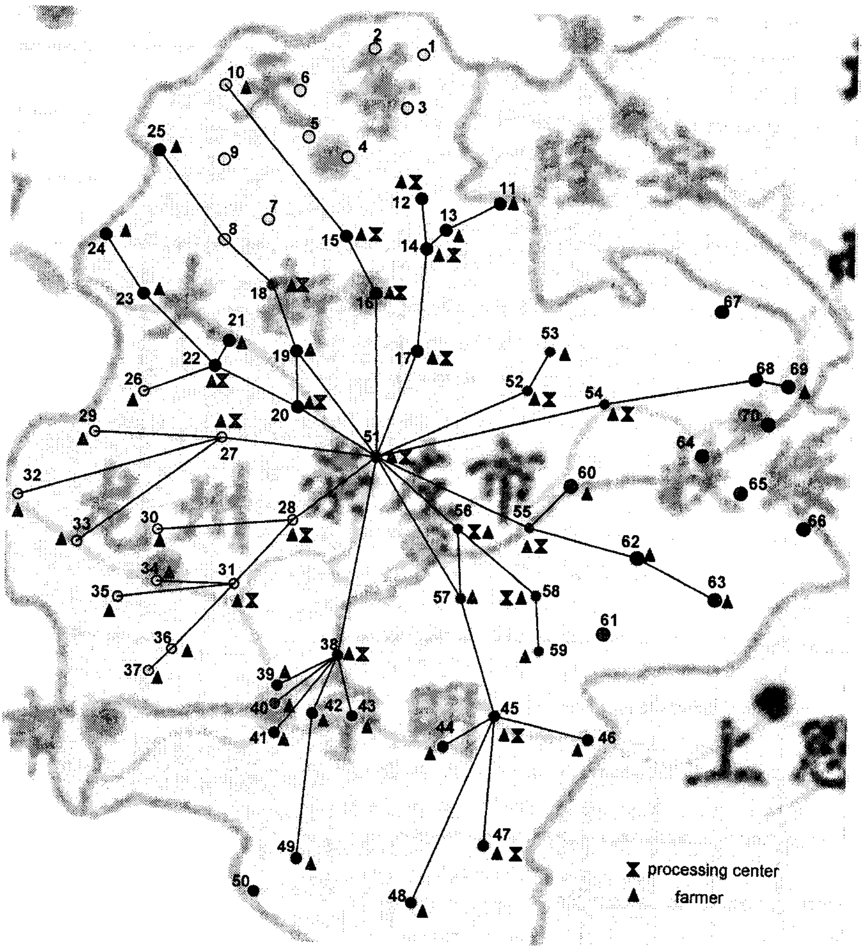


Figure 4-10 Solution at 100% Poverty Coverage, 4.4% Income Increase Rate

Table 4-7 Solution at 100% Poverty Coverage, 4.4% Income Increase Rate

	Cassava Quantity(ton)		Cassava Quantity(ton)		Cassava Quantity(ton)
10	1000	**28**	27456	46	1000
11	1000	29	1000	**47**	1000
12	32654	30	1000	48	1000
13	14358.2	**31**	21507	49	1000
14	23312.6	32	1000	**51**	83040
15	32193.2	33	1000	**52**	33529.6
16	46410	34	1000	53	27851.6
17	37305	35	1000	**54**	23812
18	49953	36	1000	**55**	22148.2
19	19118	37	1000	56	29974.6
20	52230	**38**	10755.4	57	15316.6
21	9668.6	39	1000	**58**	20334.6
22	24378.2	40	1000	59	19008.6
23	1000	41	1000	60	4754.6
24	1000	42	1000	62	1000
25	1000	43	13280.7	63	1000
26	15360.2	44	1000	69	1000
27	14261	**45**	31028.4		

4.4.2 Implementation Related Issues

This analysis is conducted to provide insights to the cassava supply network. In this thesis, we use 2,000 Yuan as the poverty level. We vary this level from 1,500 Yuan to 2,500 Yuan to observe the effect of the poverty level changes on the number of poor farmers covered, the average income increase rate and the total system cost. The results are listed in Figure 4-8. At each poverty level, all poor farmers are covered by the project. The income increase rate declines from 15.8% to 6.2% following the reverse trend of the poverty coverage. In the case that only small portions of farmers are targeted for income generation, those farmers can gain greater benefits from cassava planting. For example, with our current data at the poverty level of 1,500 Yuan, 12.9% farmers are in the targeted group and their revenue could increase by 213.2 Yuan from 1,565.1 Yuan to 1,351.9 Yuan on average. When 87% of the farmers are to be covered with a poverty level of 2500 Yuan, the average income increase will only be 122 Yuan from 2,095 Yuan to 1,973.3 Yuan. The results shown in Table 4-8 are plotted in Figure 4-11. One can see that the system cost rises first and then declines. The cost increases when the poverty level increases from 1,500 Yuan to 2,200 Yuan. Within this range, the population of the poor farmers increases and therefore, the amount of cassava collected from the poor farmers increases accordingly in order to reach the maximum income increase rate. As the locations of most poor farmers are far from the manufacturing plant, the transportation cost increases with the enlargement of cassava collection quantities from the poor farmers to the plant. This cost declines when the poverty level is defined at 2,300 Yuan or above. At the poverty level of 2,200 Yuan or above, poor farmers have capacity to provide 100% or even more cassava to the manufacturing plant. Because almost all the supply points can be categorized as the poor at these poverty levels, the system chooses the suppliers based on the distance to minimize the cost. Decision makers can weigh these three factors from Fig. 4-11 to select target groups for income generation.

We also noted that with the current data, the strategy that only relies on developing cassava industry for poverty relief in this area should be reconsidered. The reason is that under all of the poverty levels with the exception of the first two, the average income of the farmers after participating in the program is still below the prescribed level. For example, the average income of poor farmers would be 1,812.3 Yuan after the program was implemented if farmers with average income equal to or lower than 2,000 Yuan were covered. The average income of 1,812.3 Yuan is below the poverty level of 2,000 Yuan. This can be attributed to two reasons. First, the cassava production capacity of poor farmers hinders their income increase. At the poverty level of 1,700 Yuan, only 43% cassava comes from farmers whose income is below or equal to such level as shown in Table 4-8. Those farmers lack of sufficient cassava production capacity to satisfy the whole demand of the manufacturing plant and thus have a limit on their income increase. The manufacturing plant capacity is another constraint. Fixed revenue is gained by farmers who supply cassava to the manufacturing plant with a capacity of 100,000 tons. Although all the cassava crops are supplied from the poor farmers at the poverty level of 2,200 Yuan, the income increase distributed to each farmer is still very low with the number of poor farmers covered by the program increases. The average income per capita will be 1,966.2 Yuan after the program is implemented and is still below the poverty level of 2,200 Yuan.

Table 4-8 Percentage of the Poor to the Total Population, Average Income Increase Rate and Cost at Different Poverty Levels

	Poverty Level		Percentage of the Poor to the Total Population	Average Income Increase rate	Average Income of the Poor				Cost (Yuan)	Percentage of Cassava Quantity from the Poor
					Before		After			
	(Yuan)	(CAD)			(Yuan)	(CAD)	(Yuan)	(CAD)		
1	1500	300	12.9%	15.8%	1351.9	270.4	1565.1	313	7,544,765	26%
2	1600	320	17.8%	15.1%	1408.4	281.7	1621	324.2	7,894,291	36%
3	1700	340	23.4%	13.3%	1465.6	293.1	1660.5	332.1	8,366,740	43%
4	1800	360	29%	12.8%	1520.7	304.1	1714.9	343	8,908,028	53%
5	2000	400	38%	11.9%	1619.9	324	1812.3	362.5	9,773,244	70%
6	2100	420	50%	10.9%	1722.7	344.5	1910.5	382.1	10,650,730	88%
7	2200	440	58%	10.3%	1782.2	356.4	1966.2	393.2	10,994,480	100%
8	2300	460	74.4%	7.6%	1893.5	378.7	2036.7	407.3	8,958,648	100%
9	2500	500	87%	6.2%	1973.3	394.7	2095	419	7,500,844	100%

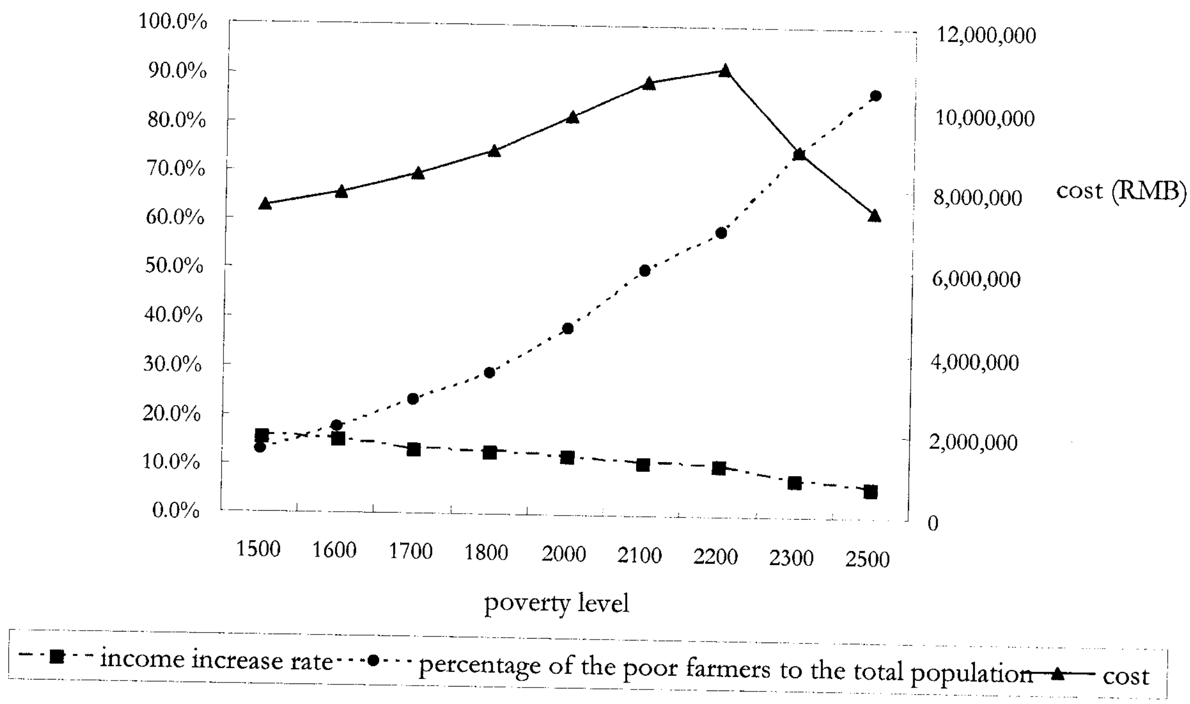
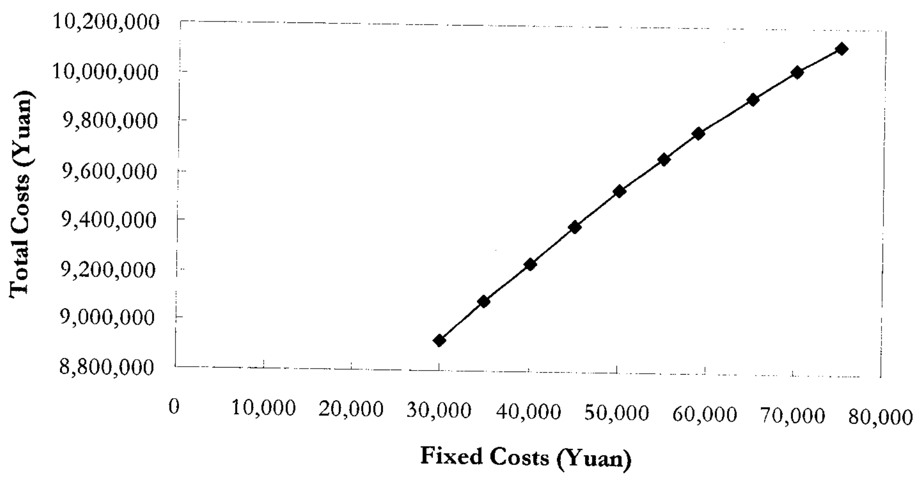


Figure 4-11 Percentage of the Poor to the Total Population, Income Increase Rate and Cost at Different Poverty Levels

The computational results of the model also demonstrate the relationship between different cost figures. An analysis conducted on the fixed cost of the processing centers shows that the total system cost increases as the fixed cost increases. Table 4-9 and Figure 4-12 list the system costs with different fixed costs at the poverty level of 2,000 Yuan. The cutoff of the fixed costs of the processing centers can be a way to accomplish cost reduction.

Table 4-9 The Fixed Cost vs. Total Cost at the Poverty Level of 2,000 Yuan

	Fixed Costs		Total Costs	
	Yuan	CAD	Yuan	CAD
1	30,000	6,000	8,921,068	1,784,214
2	35,000	7,000	9,083,524	1,816,705
3	40,000	8,000	9,240,040	1,848,008
4	45,000	9,000	9,390,285	1,878,057
5	50,000	10,000	9,538,221	1,907,644
6	55,000	11,000	9,669,298	1,933,860
7	65,000	13,000	9,918,108	1,983,622
8	75,000	15,000	10,128,440	2,025,688



4-12 The Relationship of Fixed Cost and Total Cost at the Poverty Level of 2,000 Yuan

In summary, our suggestions for the implementation of the program are:

- The cassava development strategy should be combined with other income generation strategies to achieve the goal of poverty relief; dependence on the cassava development strategy can only alleviate the poverty condition, not relieve it.
- The establishment of more ethanol manufacturing plants can help with poverty reduction. The capacity of those manufacturing plants should be within the cassava production capacity of the farmers in the area.
- Fixed cost should be carefully evaluated due to its direct impact on the system cost.

4.4.3 Protein Feed Route Planning

The vehicle routes are planned to deliver protein feed to the towns in the area after the distribution network is set up.

The feed distribution covers all 70 towns. The vehicle routing model formulated in the Chapter 3 cannot be solved directly by LINGO 8.0 due to large number of variables in the model. We then applied the Clarke and Wright algorithm to divide the processing centers into different groups and let fleet travel in small tours. The algorithm groups nodes into routes by linking nodes with the maximum distance-savings in descending order. The distances of two nodes to the original node are saved if two nodes are connected in a route. The distance saving of any two nodes is calculated by summarizing the distance of the nodes to the original node minus the distance between these two nodes. In our problem, the original node is the manufacturing plant and located in node 51. All the other nodes must be placed on the routes beginning from and ending with node 51. We code Clark & Wright algorithm in C++. The main part of the code is presented in the Appendixes. The coordinates of nodes are input in the C++ program for distance-savings calculations using an Excel data sheet.

We use 250 kilometers as the maximum travel distance. A total 11 routes are formulated. The rule that vehicles from the remote towns passes through nearby towns before arriving at the center of the area is followed. We manually combined such constraints with the results of the computer program to make the final plan of the delivery routes. The final determined routes are listed in Table 4-10. The route distances are within 247 kilometers. The routes are plotted in Figure 4-13.

Table 4-10 Routes for Feed Distribution

	Routes									Length (km)
1	51	17	14	13	11	53	52	51		170.7
2	51	12	3	1	2	4	15	16	51	224.1
3	51	5	6	10	25	9	7	18	51	243.4
4	51	19	8	24	23	21	22	20	51	196.7
5	51	27	26	29	32	33	30	51		204.6
6	51	28	34	35	37	36	31	51		175.1
7	51	39	40	41	50	49	42	51		233.5
8	51	38	43	48	47	44	51			246.8
9	51	57	45	46	61	59	58	56	51	209.2
10	51	55	62	63	66	65	60	51		234.5
11	51	64	70	69	68	67	54	51		241.8

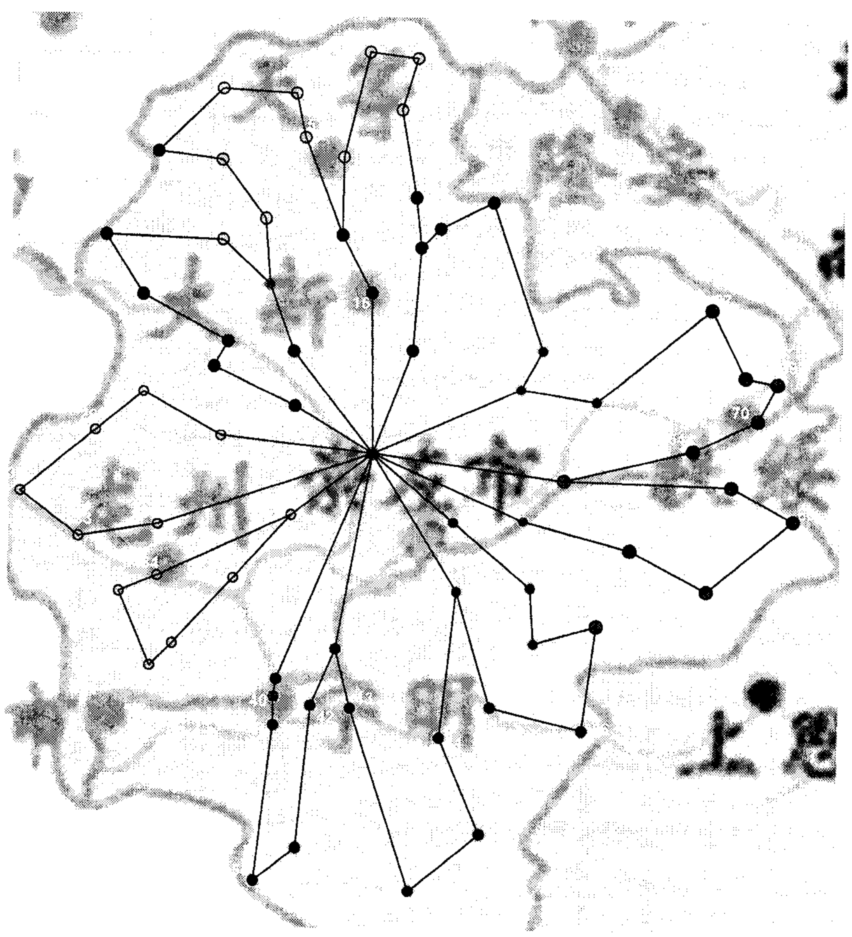


Figure 4-13 Feed Distribution Routes

4.5 Summary

The cassava supply system is set up with the resulting processing center locations and feed distribution routes. The locations of processing centers can be any of the trade-off solutions of the three objectives. Cassava crops are collected from the selected farmers and shipped to the manufacturing plant. Mud is supplied in reverse direction from the manufacturing plant to the farmers. The shipment quantities between farmers and the manufacturing plant are determined after processing centers are located. The model results are intended to be presented in front of decision makers for final decision on the cassava supply distribution system set up. The decision makers may choose to enlarge population coverage of the poor or increase their income increase rate, the cost will rise accordingly; or they may choose to reduce the cost with fewer covered poor farmers or with lower income increase rate.

Chapter 5

Conclusion and Future Research

5.1 Conclusions

China initiated a cassava development strategy for poverty alleviation in rural areas in Guang'xi province in 2000. The strategy is to promote the industrialized operation of cassava agriculture to ensure revenues for poor farmers in the province. In response to this made-to-order farming strategy, a 500,000 ton cassava-ethanol manufacturing enterprise will be established in the next 5 years. The material supply network for the establishment of a 100,000 ton cassava-ethanol manufacturing plant is studied in this thesis. The thesis objective is to build a model to optimize material supply for the manufacturing plant. A cassava supply system involves farmers, processing centers and the manufacturing plant. Cassava and mud are transported between farmers and the manufacturing plant through processing centers. The establishment of an efficient cassava supply system is vital as it involves long term and large investments and requires financial assistance from the government. The model is formulated as a mixed integer linear programming model. It extends from the fixed charge facility location model and incorporates multicriteria decision making. The multiple objectives are comprised of poverty population coverage, average income increase rate of the poor and the total system operation cost. The results of the model provide information on

- Locations of processing centers and storage capacities of the centers.
- Farmers to be covered by the program and assignment to the processing centers.

- Amount of cassava collected from the farmers and shipped to processing centers.
- Amount of cassava shipped from the processing centers to the manufacturing plant.
- Amount of mud shipped from the manufacturing plant to the processing centers.
- Amount of mud shipped from the processing centers to the farmers.

The integer programming model is flexible to allow new constraints to be added to accommodate on-site implementation requests. Furthermore, it provides insight to the configuration of the supply network. As the feed distribution is also a part of the transportation task, optimal vehicle routes of feed shipment are planned by utilizing a vehicle routing model.

The multi-objective model is solved using the constraint method. The trade-off solutions of poverty coverage, income increase rate and system cost are determined by setting different target values of the objectives. The model has more than 10, 000 variables and 20, 000 constraints. The developed model offers a framework to assist decision makers in making final decisions regarding the material supply strategy. Our research focuses on developing the model rather than discussing the advantages or disadvantages of any particular solution strategies.

5.2 Future Research

Our suggestions for future research in this area include more extensive model formulation and developing more effective and efficient heuristic methods to solve these models.

In this thesis, we studied a material supply problem of a single time period. A multi-period facility location model can be formulated to set up several manufacturing plants and processing centers in several time periods. The decision concerning the time for the establishment of the new processing centers and for the expansion of existing processing centers, as well as determination of their optimal locations will be made to provide full vision of future development of the material supply network. To solve such a complicated multi-period location model, one must develop efficient solution method rather than relying on off-shelf optimizing software.

The developed material supply plan requires further adjustment before it can be implemented. Additional constraints may be added and new factors may be included. As the project progresses, the supply network will extend to the supply chain, including ethanol production and distribution. The problem of coordinating material supply, production and finished products distribution should be studied.

As for the solution method, metaheuristic procedures including Simulated Annealing or Tabu search for solving location-allocation problems can be developed. In addition, incorporating GUI-type (Graphic User Interface) programs to the location model can provide flexible and convenient tools for analysts' or decision-makers' interaction with the model and thus is another interesting topic for future research.

The correctness of the estimated data such as cost parameters may affect the output of the mixed integer programming model. We plan to conduct the sensitivity analysis of the model to further investigate such effect.

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Appendix A

Model Linearization

Some non-linear formulations exist in the model; they are linearied to be applied in LINGO.

We take the second objective of the processing location model as an example. Both XC_j and Y_j are variables in the objective function.

We let $$V = \frac{pro \sum_{j=1}^{N} l_j XC_j}{\sum_{j=1}^{N} l_j Y_j p_j inc_j} \tag{a.1}$$

where V is maximum value of Z_2.

The equation is rewritten to be

$$V \sum_{j=1}^{N} l_j Y_j p_j inc_j = \sum_{j=1}^{N} l_j XC_j pro \tag{a.2}$$

V can be included into summation,

$$\sum_{j=1}^{N} V\, l_j Y_j p_j inc_j = \sum_{j=1}^{N} l_j XC_j pro \tag{a.3}$$

We let $TEMP_j = V\, l_j Y_j p_j inc_j$,

implies that

$$TEMP_j = \begin{cases} V\, p_j inc_j, & \text{if } l_j Y_j = 1 \\ 0, & \text{if } l_j Y_j = 0 \end{cases}$$

Now the equation (a.1) can be expressed by the following three inequalities:

$$TEMP_j \geq V\ p_j inc_j + M\ l_j Y_j - M \tag{a.4}$$

$$TEMP_j \leq V\ p_j inc_j \tag{a.5}$$

$$TEMP_j \leq M\ l_j Y_j \tag{a.6}$$

$$\text{where } \sum_{j=1}^{N} TEMP_j = \sum_{j=1}^{N} l_j XC_j pro \tag{a.7}$$

M is a large positive number. Equality (a.4) and (a.5) enforces $TEMP_j$ to be $V\ p_j inc_j$ when $l_j Y_j$ is 1. Equality (a.6) enforces $TEMP_j$ will be 0 when $l_j Y_j$ is 0. Combined with equation (a.7), we can obtain that V will be $\frac{\sum_j l_j XC_j pro}{\sum_j p_j inc_j}$ when $l_j Y_j$ is 1 and 0 when $l_j Y_j$ is 0.

The nonlinear function in 3rd objective, $\sum_{j=1}^{N} XC_j Z_{i,j} = STOR_i$, is linearized following the same rule.

Appendix B

List of Data in the Processing Center Location Problem

$pl =$ 2000 (Yuan, 400 CAD).

$d =$ 780,000 (ton).

$pro =$ 180 (Yuan per ton, 36 CAD per ton).

$f_i =$ 590,000 (Yuan, 118,000 CAD).

$sc =$ 0.1 (Yuan per ton, 0.02 CAD per ton).

$tc =$ 0.3 (Yuan per km per ton, 0.06 CAD per km per ton).

$r =$ 0.3333.

$\bar{\alpha} =$ 0.5%.

$col =$ 1000 (ton).

$mprod =$ 60,000 (ton).

Nodes' Distance Table (km)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
1	0.0	14.1	25.0	20.2	26.9	29.5	45.6	57.4	48.7	47.2	35.6	27.7	36.0	40.4	42.3	53.5	66.9	63.0	74.5	87.3	81.3	88.6	88.6	89.2	69.4	95.6	92.5	106.9
2		0.0	20.7	32.8	36.4	34.2	57.7	69.1	57.3	51.5	45.6	41.5	49.1	54.1	56.1	67.5	80.5	76.3	88.4	101.4	94.6	101.9	100.2	99.0	77.4	108.2	106.3	120.9
3			0.0	32.0	28.2	19.5	51.3	61.0	44.3	33.8	60.5	49.3	58.9	61.9	56.6	71.3	88.6	72.6	87.7	101.7	90.1	97.4	90.6	86.1	62.4	101.1	104.1	123.6
4				0.0	11.7	22.0	25.4	37.3	31.3	36.0	39.9	21.2	31.2	32.1	24.9	39.4	55.9	43.6	56.8	70.4	61.8	69.1	68.4	69.8	52.0	75.5	74.1	91.7
5					0.0	12.4	23.2	33.5	21.7	24.4	51.6	32.5	42.4	42.6	30.7	46.9	64.4	44.5	60.2	74.3	61.9	69.3	64.1	62.7	42.5	73.4	76.1	97.0
6						0.0	33.6	42.1	24.9	17.8	60.2	43.1	53.2	54.1	43.0	59.3	76.7	55.4	71.8	86.0	72.2	79.4	71.2	66.8	43.7	82.1	87.1	109.0
7							0.0	12.0	19.3	35.2	56.7	35.2	42.1	38.5	18.4	33.6	51.7	21.9	39.0	53.2	38.8	46.1	43.1	46.1	34.1	50.7	53.5	76.9
8								0.0	21.0	38.8	67.6	46.3	52.3	47.8	27.0	39.1	56.1	18.2	36.4	50.7	31.1	38.0	31.2	34.6	27.5	40.1	47.5	74.2
9									0.0	17.8	69.8	48.8	57.5	55.3	36.8	52.9	71.1	38.3	56.5	71.7	52.1	58.8	46.8	42.0	20.9	59.0	68.5	94.5
10										0.0	75.8	56.8	66.5	66.0	50.4	67.0	85.2	56.1	73.8	89.5	69.9	76.5	62.8	54.5	29.6	76.0	86.3	111.8
11											0.0	21.6	16.6	23.3	41.6	41.1	44.1	63.0	65.5	74.4	78.9	85.1	95.2	102.2	89.4	96.4	83.7	87.6
12												0.0	10.1	12.8	21.5	26.9	39.2	43.9	50.5	62.0	61.1	67.9	74.9	80.9	68.0	77.8	69.1	79.9
13													0.0	6.9	25.5	24.2	33.4	46.4	49.3	59.2	62.2	68.5	78.8	86.7	75.9	79.8	67.7	74.7
14														0.0	20.8	17.3	26.5	40.4	42.4	52.3	55.6	61.8	73.1	81.8	72.6	73.3	60.8	68.3
15															0.0	16.6	34.8	22.5	32.3	45.6	40.2	47.3	53.7	61.2	52.4	56.5	50.2	67.0
16																0.0	18.2	26.5	25.2	35.3	39.3	45.1	59.2	79.3	66.3	57.4	43.5	53.4
17																	0.0	40.7	30.8	33.7	48.0	51.7	71.3	84.8	83.5	65.8	45.4	43.5
18																		0.0	18.3	32.5	18.3	25.6	32.9	44.3	44.8	33.9	31.7	56.3
19																			0.0	14.2	17.3	21.1	41.6	57.1	62.2	34.9	18.6	38.1
20																				0.0	24.2	23.4	49.4	67.5	78.2	37.7	12.6	24.3
21																					0.0	7.4	25.0	41.7	52.0	18.1	17.1	47.2
22																						0.0	26.0	43.8	57.0	14.5	13.1	44.2
23																							0.0	18.1	36.9	16.0	39.1	70.2
24																								0.0	25.3	33.6	56.9	88.0
25																									0.0	52.1	69.1	98.6
26																										0.0	26.1	56.5
27																											0.0	31.1
28																												0.0

Nodes' Distance Table(continued)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
29	113.7	126.2	118.3	93.6	91.0	99.1	68.5	57.6	75.2	91.5	114.0	95.9	97.4	90.8	74.6	74.4	80.8	52.0	50.5	49.4	35.2	32.7	28.7	42.2	65.1	18.2	36.8	62.6
30	124.2	137.9	134.7	105.5	106.5	116.8	83.4	75.3	95.9	113.5	114.7	100.9	99.1	92.2	82.0	74.9	73.5	62.2	50.4	40.3	44.6	37.4	55.2	72.1	91.4	39.4	31.9	39.2
31	129.2	143.3	143.9	112.7	116.3	127.9	94.6	89.3	110.3	128.1	112.2	103.1	98.6	92.1	87.8	76.2	68.2	72.8	56.2	42.3	58.7	53.1	76.5	94.4	110.1	60.8	41.8	25.0
32	142.0	154.4	145.7	121.8	118.8	126.3	96.7	85.4	101.9	117.2	141.9	124.1	125.3	118.6	102.9	101.9	106.3	80.4	77.2	73.2	63.1	56.8	55.1	64.2	89.1	46.6	61.0	80.7
33	140.3	153.4	147.6	120.6	119.7	128.7	96.6	86.6	105.6	122.4	134.7	119.2	118.6	111.7	98.9	94.4	95.4	77.2	69.3	61.7	59.0	51.7	60.0	73.5	96.6	46.7	51.1	62.7
34	137.3	151.2	148.8	119.0	120.6	131.2	97.7	89.9	110.6	128.3	125.4	113.1	110.4	103.5	95.1	86.5	82.7	76.2	62.9	51.2	59.0	52.0	69.9	86.6	106.2	54.2	45.0	43.1
35	146.7	160.4	156.9	127.9	128.7	138.8	105.6	97.0	117.2	134.6	136.4	123.2	121.1	114.2	104.5	97.0	94.1	84.6	72.8	62.0	66.8	59.5	74.1	89.5	110.9	59.0	54.4	55.2
36	153.2	167.2	166.3	135.7	138.2	149.2	115.6	108.7	129.6	147.3	137.9	127.8	123.9	117.2	111.2	100.8	94.0	93.8	79.0	65.9	77.6	70.8	89.9	106.7	126.0	74.1	62.2	51.0
37	161.7	175.7	174.2	144.0	146.1	156.9	123.4	115.9	136.7	154.4	147.0	136.5	132.9	126.1	119.6	109.6	103.2	101.7	87.4	74.6	84.9	78.0	95.7	111.9	132.2	80.1	70.1	60.2
38	140.0	153.9	158.0	126.0	131.8	143.9	112.0	109.1	129.6	146.9	116.6	112.4	105.9	100.1	101.5	86.9	73.8	91.3	73.2	59.2	80.7	76.4	101.5	119.5	132.6	86.3	63.7	35.1
39	150.4	164.4	166.7	135.0	139.6	151.4	118.4	113.8	134.8	152.5	129.6	123.3	117.7	111.5	110.1	96.9	85.9	96.9	79.6	65.4	83.6	78.1	101.5	119.3	135.2	85.6	66.6	43.5
40	154.9	169.0	171.2	139.6	144.1	155.9	123.0	118.3	139.2	156.9	134.0	127.9	122.2	116.0	114.7	101.5	90.3	101.4	84.1	69.9	88.0	82.4	105.5	123.2	139.4	89.6	71.0	48.0
41	162.1	176.2	178.6	146.9	151.5	163.3	130.3	125.6	146.6	164.3	140.8	135.0	129.2	123.1	122.0	108.7	97.3	108.7	91.5	77.3	95.2	89.6	112.4	130.0	146.6	96.5	78.3	55.3
42	155.4	169.4	172.9	141.0	146.3	158.3	125.8	122.0	142.8	160.4	132.6	128.0	121.7	115.8	116.3	102.2	89.6	104.6	86.8	72.6	92.4	87.4	111.4	129.3	144.3	95.7	75.3	49.3
43	154.8	168.7	173.3	141.4	147.4	159.6	127.8	124.9	145.4	162.8	130.1	127.2	120.2	114.7	117.0	102.1	88.2	107.1	89.0	75.1	96.3	91.8	116.6	134.7	148.3	101.3	79.3	50.9
44	162.0	175.3	182.6	151.0	158.4	170.8	140.9	139.8	159.4	176.1	133.4	134.4	126.2	121.6	127.7	111.7	95.5	121.6	103.3	90.4	113.5	110.0	135.7	153.7	164.8	120.9	97.0	66.3
45	155.5	168.4	177.2	146.1	154.4	166.7	138.5	138.6	157.4	173.5	125.1	128.3	119.5	115.5	123.9	107.5	90.2	120.5	102.6	90.6	114.6	112.0	138.0	155.8	164.7	124.1	98.9	67.8
46	166.3	178.3	189.4	159.4	168.7	180.8	155.0	156.6	174.2	189.4	133.3	140.1	130.6	127.7	139.1	122.4	104.4	138.7	121.4	110.7	134.9	133.0	159.0	176.5	183.4	145.8	120.1	91.9
47	187.9	201.0	209.0	177.6	185.3	197.6	168.1	167.0	186.6	203.3	158.0	160.4	151.9	147.6	154.6	138.5	121.8	148.8	130.6	117.5	140.5	136.8	162.2	180.3	192.0	147.2	123.8	93.4
48	201.4	215.0	221.3	189.4	196.1	208.4	177.2	174.6	195.0	212.2	173.7	173.7	165.9	161.0	165.5	150.0	134.6	156.7	138.5	124.7	146.0	141.3	165.7	183.7	198.0	150.1	128.9	100.5
49	192.4	206.4	209.9	178.0	183.1	195.1	162.4	157.9	178.9	196.5	168.8	165.0	158.4	152.7	153.3	139.2	126.4	140.9	123.4	109.2	127.6	122.0	144.5	162.0	178.9	128.5	110.6	86.4
50	202.6	216.6	219.2	187.4	192.0	203.7	170.6	165.4	186.4	204.2	180.1	175.3	169.2	163.2	162.6	149.2	137.2	148.9	131.9	117.7	134.7	128.6	149.8	166.9	185.2	133.9	117.9	95.8
51	89.0	102.9	108.0	76.2	83.2	95.6	66.3	68.6	85.3	101.4	66.6	62.2	60.9	49.4	53.3	36.7	22.9	50.4	32.1	24.6	48.8	48.0	74.0	92.1	93.7	62.2	36.9	21.8
52	77.8	89.2	101.9	74.6	85.4	96.6	78.9	85.5	97.1	108.8	43.9	53.7	43.6	42.9	60.5	46.4	31.8	71.9	62.4	62.6	79.7	82.9	103.1	116.2	112.4	97.2	75.0	62.7
53	71.3	81.7	96.0	70.9	82.2	92.7	78.9	86.9	96.1	106.2	36.0	49.7	39.8	40.9	60.5	48.6	37.4	75.0	68.1	70.2	85.0	89.0	107.3	119.1	112.9	103.0	82.4	72.9
54	89.9	99.6	114.7	90.1	101.4	112.0	97.3	104.7	115.0	125.4	54.3	69.0	59.0	59.8	78.9	65.8	51.7	91.6	82.2	81.7	99.5	102.6	122.9	135.9	131.2	117.0	94.3	78.9
55	110.4	122.5	133.6	104.1	113.9	125.8	102.4	105.9	121.6	135.6	77.8	84.4	74.8	72.1	85.3	68.9	50.7	89.1	74.0	67.3	90.2	90.7	115.2	131.1	133.4	105.0	79.3	54.5
56	107.2	120.3	128.8	97.8	106.4	118.7	91.9	93.8	111.2	126.5	78.0	79.8	71.2	67.0	76.3	59.7	42.0	76.2	59.6	51.1	74.7	74.5	99.7	116.3	120.9	88.5	62.5	36.4

Nodes' Distance Table(continued)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
57	124.8	137.9	146.2	115.0	123.2	135.6	107.7	108.6	126.8	142.7	95.5	97.4	88.8	84.6	92.9	76.4	59.1	90.5	73.0	62.3	86.5	85.0	110.8	128.2	135.1	98.2	72.2	42.1
58	127.4	139.7	150.4	120.5	129.9	142.0	117.0	119.6	136.3	151.0	95.1	101.1	91.7	88.7	100.6	84.0	65.8	102.1	85.7	76.9	100.8	100.2	125.6	142.4	146.8	114.0	87.9	59.4
59	141.3	153.7	164.1	133.8	143.0	155.2	129.2	131.0	148.5	163.6	109.2	114.8	105.5	102.3	113.3	96.6	78.6	113.2	96.2	86.1	110.2	108.9	134.7	152.0	158.0	122.2	96.2	66.1
60	104.0	115.2	128.2	100.4	110.9	122.4	102.3	107.4	121.1	133.8	69.7	79.7	69.7	68.4	84.3	68.7	51.4	91.8	78.8	74.5	95.7	97.3	120.4	135.3	134.8	111.8	86.9	65.5
61	141.9	153.4	165.6	136.7	146.6	158.5	135.2	138.3	154.4	168.5	107.9	116.6	106.8	104.6	118.2	101.7	83.5	121.1	105.1	96.6	120.4	119.9	145.3	161.9	165.7	133.7	107.6	78.9
62	127.6	138.1	152.0	124.9	135.5	146.9	127.0	131.8	145.8	158.6	92.5	104.1	94.0	93.0	109.1	93.4	75.8	115.8	101.7	95.7	118.2	119.1	143.2	158.7	159.3	133.5	107.8	82.6
63	146.5	156.2	171.3	145.4	156.3	167.4	148.8	154.0	167.5	179.8	111.0	124.4	114.3	113.9	130.7	115.4	98.0	138.2	124.2	118.0	140.7	141.4	165.6	181.2	181.4	155.8	130.0	103.8
64	115.1	123.4	140.1	117.3	128.8	138.9	125.4	132.7	142.9	152.9	79.7	96.2	86.4	87.7	107.0	93.7	78.8	119.2	108.8	106.7	126.1	128.7	150.1	163.5	159.3	143.2	119.3	99.7
65	128.6	136.7	153.6	130.8	142.3	152.4	138.6	145.6	156.3	166.5	93.2	109.8	99.9	101.1	120.2	106.5	91.1	131.7	120.6	117.5	137.8	139.9	162.0	175.9	172.4	154.5	130.0	108.5
66	145.9	153.5	170.8	148.8	160.3	170.3	156.9	163.9	174.5	184.5	110.7	127.8	118.0	119.3	138.4	124.8	109.2	149.9	138.3	134.7	155.5	157.4	179.9	194.0	190.6	172.0	147.2	124.3
67	94.3	99.3	118.4	102.4	114.0	121.9	117.4	127.1	132.1	138.2	62.5	83.3	75.3	79.3	100.1	91.4	82.3	117.8	112.8	115.3	129.4	133.8	150.7	160.9	151.1	147.5	127.4	116.0
68	111.5	117.4	136.0	117.7	129.4	138.1	130.2	139.1	146.2	153.7	78.0	97.6	88.7	91.7	112.3	101.5	89.5	127.9	120.4	120.7	137.5	141.1	160.2	171.9	164.3	155.3	133.2	117.4
69	119.2	124.7	143.5	125.9	137.5	146.1	138.7	147.6	154.5	161.9	86.0	105.9	97.1	100.2	120.7	110.0	98.8	136.4	128.7	128.8	145.9	149.4	168.6	180.4	172.7	163.6	141.4	124.9
70	121.3	127.8	146.0	126.2	137.9	147.1	137.2	145.4	153.8	162.2	86.9	105.7	96.4	98.8	119.0	107.1	93.7	133.2	124.3	123.2	141.5	144.6	164.9	177.5	171.3	159.0	135.9	117.7

Nodes' Distance Table(continued)

	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56
29	0.0	33.2	59.2	28.4	31.5	46.2	47.6	66.1	70.4	86.8	82.5	85.9	92.1	93.4	100.5	122.2	127.5	150.6	147.4	147.3	123.0	126.6	73.4	111.5	118.2	130.9	115.0	97.6
30		0.0	27.1	41.5	23.6	14.9	22.5	34.7	41.0	55.0	49.4	52.7	59.0	60.4	67.8	90.4	97.2	121.0	114.8	114.2	90.3	94.8	57.5	99.3	108.4	116.9	93.6	75.4
31			0.0	67.5	48.1	22.3	34.4	26.0	35.2	27.9	25.1	29.7	37.1	36.5	41.3	63.4	70.3	94.4	88.1	89.3	69.5	76.2	46.9	87.0	97.6	102.1	73.2	55.6
32				0.0	21.6	47.2	41.1	62.8	63.4	94.9	85.5	87.7	92.4	96.9	105.7	129.5	137.7	161.9	152.1	147.6	119.6	120.1	97.9	135.7	143.4	154.5	134.2	116.2
33					0.0	25.8	19.9	41.5	42.9	73.9	64.0	66.2	70.9	75.3	84.3	108.2	116.8	141.1	130.5	126.2	98.7	100.1	80.8	122.4	131.2	140.3	116.9	98.8
34						0.0	12.1	20.1	26.1	48.2	38.6	41.2	46.7	50.0	58.6	82.4	91.1	115.5	105.1	102.3	76.8	80.5	64.9	105.6	115.5	122.0	95.0	77.1
35							0.0	21.7	23.3	57.7	45.6	47.2	51.4	56.8	66.2	90.5	100.3	124.8	111.6	106.5	78.8	80.5	75.9	117.7	127.5	134.1	106.9	89.0
36								0.0	9.2	40.7	25.7	26.4	29.9	36.3	46.2	70.6	81.8	106.2	90.4	84.7	57.6	60.5	72.9	112.7	123.4	126.9	96.0	79.3
37									0.0	48.1	31.8	31.4	32.9	41.2	51.4	75.5	87.6	111.8	93.3	85.3	56.3	57.2	82.1	121.8	132.6	135.9	104.5	88.1
38										0.0	17.3	20.2	25.4	16.0	15.8	35.5	42.9	67.3	61.0	65.5	53.1	63.6	51.1	82.3	93.7	92.8	58.5	44.4
39											0.0	4.6	11.9	11.4	20.7	45.1	56.1	80.5	66.5	64.9	44.4	52.5	68.4	97.9	109.3	109.5	75.7	60.9
40												0.0	7.4	9.9	20.1	44.3	56.3	80.4	64.4	61.4	39.7	47.9	73.0	101.8	113.2	113.0	78.7	64.5
41													0.0	10.9	20.4	43.2	56.4	80.1	60.7	55.6	32.4	40.6	80.4	107.7	119.1	118.1	83.2	69.8
42														0.0	10.2	34.4	46.6	70.6	55.2	54.4	37.1	47.6	67.1	98.0	109.5	107.8	72.6	59.7
43															0.0	24.4	36.3	60.4	47.0	49.7	38.8	51.1	66.9	93.4	104.9	101.5	65.7	54.6
44																0.0	15.3	37.0	27.2	40.4	46.9	60.7	79.5	92.3	103.4	95.7	59.7	55.4
45																	0.0	24.5	33.0	51.9	62.1	75.9	72.7	82.4	93.1	83.5	48.6	48.5
46																		0.0	37.7	61.0	80.1	93.5	89.7	89.4	98.6	84.8	55.9	63.0
47																			0.0	23.4	47.9	59.8	102.2	115.4	126.0	115.7	81.5	80.7
48																				0.0	31.4	40.4	113.2	132.7	143.7	135.3	99.7	95.6
49																					0.0	13.7	103.6	132.0	143.4	139.0	102.7	93.2
50																						0.0	114.3	144.4	155.9	152.1	115.9	105.7
51																							0.0	41.9	53.4	59.6	42.9	27.5
52																								0.0	11.5	19.9	34.3	38.7
53																									0.0	19.2	44.6	50.2
54																										0.0	36.4	48.6
55																											0.0	18.1
56																												0.0

Nodes' Distance Table(continued)

	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56
57	104.6	78.1	54.1	119.7	100.5	76.4	87.6	74.0	82.1	34.6	51.8	54.5	58.6	47.8	40.7	37.9	31.1	48.4	63.1	78.3	79.5	91.2	41.6	54.8	66.1	61.0	24.9	17.7
58	121.9	96.8	73.2	138.2	119.4	95.6	106.8	92.9	100.7	52.8	69.8	72.1	75.3	64.4	55.9	45.1	32.3	39.0	64.9	84.1	90.4	104.0	53.7	51.5	61.5	51.1	17.2	26.1
59	128.4	100.9	75.5	142.4	122.5	97.6	108.2	92.0	99.1	51.3	67.3	68.7	70.6	59.9	50.4	34.4	20.0	25.8	51.3	71.6	81.1	94.9	67.7	65.6	75.6	64.4	31.4	37.3
60	123.5	104.7	86.2	144.5	128.2	107.5	119.5	109.8	118.5	73.2	90.3	93.4	98.0	87.4	80.5	73.5	61.3	64.4	93.7	113.1	117.4	130.6	50.1	26.3	34.2	22.2	14.9	30.6
61	141.5	115.5	91.0	157.1	137.7	113.3	124.1	108.6	115.8	67.9	84.2	85.6	87.5	76.8	67.3	49.8	34.6	27.2	61.7	83.9	96.7	110.4	73.1	64.2	72.5	57.8	32.9	45.6
62	143.6	121.3	99.4	162.3	144.5	121.6	133.1	120.1	128.1	80.2	97.3	99.5	102.6	91.7	82.9	68.8	54.1	47.9	82.8	104.7	115.5	129.2	71.2	50.4	56.5	39.5	28.6	46.3
63	165.5	142.0	118.9	183.4	164.9	141.2	152.4	137.8	145.3	97.2	113.7	115.3	117.3	106.6	97.0	78.7	63.4	48.1	85.8	109.0	125.2	138.9	93.6	71.0	75.3	56.7	50.7	67.9
64	156.1	138.8	120.4	178.1	162.4	141.8	153.8	143.6	152.1	105.6	122.9	125.6	129.6	118.7	110.7	98.8	84.3	77.5	113.2	135.2	145.1	158.7	84.4	47.4	46.9	28.1	47.6	64.8
65	166.7	147.7	127.8	187.8	171.2	149.6	161.5	149.8	158.1	110.6	127.8	130.2	133.5	122.6	113.9	99.3	84.3	73.6	110.7	133.4	146.2	159.9	93.5	60.1	60.3	41.3	54.6	72.6
66	183.7	163.4	142.2	204.0	186.8	164.4	176.0	163.1	171.0	123.0	139.9	141.9	144.5	133.6	124.4	107.2	91.9	76.7	114.4	137.7	153.9	167.6	110.4	78.3	78.5	59.5	69.9	88.0
67	163.1	152.9	139.7	188.4	175.9	159.0	171.1	164.9	173.9	130.9	147.7	151.1	156.1	145.7	139.1	131.0	117.6	113.7	148.2	169.3	175.8	189.2	95.5	53.6	45.1	38.2	73.4	86.7
68	169.7	155.8	139.7	193.6	179.3	160.3	172.4	163.8	172.6	127.2	144.4	147.4	151.7	140.9	133.3	122.2	107.9	100.5	136.7	158.7	168.3	181.9	98.7	58.2	52.9	39.1	68.7	84.6
69	177.9	163.5	146.8	201.6	187.0	167.6	179.7	170.6	179.3	133.3	150.6	153.4	157.5	146.7	138.8	126.5	111.9	102.8	139.6	162.0	173.0	186.7	107.2	66.5	61.4	47.6	74.9	91.4
70	172.6	156.6	138.8	195.4	180.2	160.0	172.0	162.1	170.7	124.1	141.4	144.1	148.0	137.1	129.0	116.0	101.3	91.9	128.7	151.2	162.7	176.4	100.2	61.9	58.6	42.0	66.1	83.2

	57	58	59	60	61	62	63	64	65	66	67	68	69	70
57	0.0	19.2	24.0	39.8	37.4	46.1	64.8	71.2	76.1	89.1	98.4	93.1	99.0	89.6
58		0.0	14.1	29.0	19.7	27.5	45.6	55.0	58.2	70.2	86.0	78	83.1	73.1
59			0.0	42.5	16.9	34.4	46.7	64.4	65.1	74.2	97.7	87.9	92.1	81.6
60				0.0	38.3	24.8	46.6	34.3	43.4	60.3	58.6	54.2	60.8	52.6
61					0.0	21.1	29.8	51.5	49.9	57.6	86.9	75	78.2	67.4
62						0.0	22.5	30.5	31.0	43.0	65.9	54	57.8	47.2
63							0.0	36.4	27.7	28.8	72.8	56.4	56.8	46.0
64								0.0	13.6	31.6	37.0	23.6	28.0	18.5
65									0.0	18.3	46.2	28.8	29.4	18.5
66										0.0	58.6	39.4	35.9	27.6
67											0.0	19.4	25.6	31.1
68												0	8.5	11.8
69													0.0	10.9
70														0.0

Appendix C

Trade-off Solutions of Processing Center Location Problem

Index		Poverty Coverage	Average Income Increase Rate	Cost(Yuan)	Percentage of Cassava Quantity from Poverty Supply Points	Number of Supply Points	Number of Processing Centers
1	1	1	0.119	9,773,244	70%	39	25
	2		0.106	9,002,343	62%	40	22
	3		0.094	8,439,092	55%	42	21
	4		0.082	8,046,913	48%	46	19
	5		0.069	7,744,455	40%	48	20
	6		0.044	7,447,331	26%	53	19
2	1	0.939	0.124	9,642,217	68%	37	25
	2		0.111	8,917,061	61%	39	22
	3		0.097	8,317,860	53%	41	21
	4		0.072	7,691,592	40%	46	19
	5		0.046	7,424,504	25%	50	19
3	1	0.895	0.129	9,597,798	67%	37	25
	2		0.113	8,723,130	59%	38	22
	3		0.097	8,155,068	50%	41	20
	4		0.072	7,605,125	37%	45	19
	5		0.049	7,429,310	25%	50	19
4	1	0.846	0.134	9,465,491	66%	34	26
	2		0.116	8,583,307	56%	37	22
	3		0.097	8,015,949	47%	41	20
	4		0.072	7,532,340	35%	45	19
	5		0.05	7,410,437	25%	48	19
5	1	0.799	0.139	9,336,538	64%	34	25
	2		0.118	8,345,184	55%	36	22
	3		0.097	7,843,679	45%	38	20
	4		0.072	7,460,903	33%	42	19
	5		0.055	7,377,917	25%	46	18
6	1	0.749	0.143	9,246,415	62%	33	25
	2		0.12	8,203,858	51%	37	20
	3		0.097	7,712,896	42%	40	19
	4		0.072	7,415,428	31%	43	18
	5		0.056	7,365,985	25%	43	19
7	1	0.698	0.149	9,030,442	59%	32	24
	2		0.136	8,491,773	54%	34	21
	3		0.123	8,036,320	49%	35	21
	4		0.097	7,620,870	38%	38	20
	5		0.072	7,369,782	29%	41	19
	6		0.061	7,348,332	25%	43	18

Index		Poverty Coverage	Average Income Increase Rate	Cost(Yuan)	Percentage of Cassava Quantity from Poverty Supply Points	Number of Supply Points	Number of Processing Centers
8	1	0.65	0.155	8,911,750	56%	31	22
	2		0.141	8,266,011	52%	34	21
	3		0.126	7,875,313	46%	34	20
	4		0.098	7,518,209	36%	39	19
	5		0.072	7,343,377	27%	42	18
	6		0.066	7,337,926	25%	40	18
9	1	0.598	0.16	8,770,963	53%	30	23
	2		0.147	8,181,900	49%	33	20
	3		0.131	7,804,229	44%	33	19
	4		0.1	7,450,169	33%	38	19
	5		0.073	7,334,529	25%	40	18
10	1	0.549	0.166	8,696,554	51%	30	24
	2		0.156	8,174,274	48%	32	21
	3		0.147	7,932,023	45%	31	21
	4		0.131	7,692,100	39%	34	20
	5		0.098	7,385,482	29%	38	18
	6		0.08	7,317,106	25%	38	18
11	1	0.495	0.171	8,472,664	49%	30	22
	2		0.16	7,957,389	43%	31	20
	3		0.14	7,595,563	37%	32	19
	4		0.11	7,377,920	30%	36	18
	5		0.089	7,311,385	25%	37	18
12	1	0.448	0.179	8,149,579	44%	28	22
	2		0.164	7,698,367	40%	31	19
	3		0.147	7,515,461	36%	32	17
	4		0.127	7,394,545	31%	33	18
	5		0.097	7,306,252	25%	35	18
13	1	0.399	0.187	7,945,284	41%	29	21
	2		0.166	7,507,138	36%	30	19
	3		0.15	7,396,972	32%	31	19
	4		0.128	7,319,381	28%	33	19
	5		0.112	7,295,542	25%	33	18
14	1	0.35	0.195	7,917,810	37%	29	20
	2		0.181	7,609,981	34%	31	19
	3		0.167	7,398,551	32%	29	19
	4		0.128	7,290,862	25%	35	18
15	1	0.257	0.206	7,557,709	29%	27	21
	2		0.181	7,289,789	25%	31	18

Appendix D

LINGO Code of the Processing Center Problem

Four lingo models run sequentially to achieve results of the multi-objective MIP model. The data sheet (Table 4-1) is attached to models for data input.

a. Maximize the 1st objective

```
MODEL:
SETS:
DEMANDPOINTS/1..70/: XCASSAVA, INCOME,L, Y, PRODUCTIONCAPACITY,
POPULATION;
M/1,2/:MaxPW;
ENDSETS
DATA:
PRODUCTIONCAPACITY =@ole('C:\Documents and Settings\ybai\My Documents\thesis
code\zhen0108.xls','Production');
POPULATION=@ole('C:\Documents and Settings\ybai\My Documents\thesis
code\zhen0108.xls','Population');
INCOME=@ole('C:\Documents and Settings\ybai\My Documents\thesis code\zhen0108.xls','Income');
MINREQUIRED=780000;
!780000*1.005=783900;
MAXREQUIRED=783900;
INCOMELINE=2000;
CASSAVABL=1000;
ENDDATA

[OBJ]Max =MaxPW(1);
!*****************************General Contraints******************************************;
@FOR(DEMANDPOINTS(D):XCASSAVA(D)>=CASSAVABL*Y(D));
@FOR(DEMANDPOINTS(D):XCASSAVA(D)<= PRODUCTIONCAPACITY (D)*Y(D));

@SUM(DEMANDPOINTS(D):XCASSAVA(D))>=MINREQUIRED;
```

```
@SUM(DEMANDPOINTS(D):XCASSAVA(D))<=MAXREQUIRED;
@FOR(DEMANDPOINTS(D):L(D)=@IF(INCOME(D) #LE# INCOMELINE,1,0));
@FOR(DEMANDPOINTS(D):@BIN(Y(D)));
@FOR(DEMANDPOINTS(D):@BIN(L(D)));

!*****************************1st objective*********************************************;
MaxPW(1)=@SUM(DEMANDPOINTS(D):L(D)*Y(D)*POPULATION(D))/@SUM(DEMANDPOI
NTS(D):L(D)*POPULATION(D));
END
```

b. Maximize the 2nd objective

```
MODEL:
SETS:
DEMANDPOINTS/1..70/:
XCASSAVA,INCOME,L,Y,PRODUCTIONCAPACITY,POPULATION,TEMP2;
M/1,2/:MaxPW;
ENDSETS
DATA:
PRODUCTIONCAPACITY =@ole('C:\Documents and Settings\ybai\My Documents\thesis
code\zhen0108.xls','Production');
POPULATION=@ole('C:\Documents and Settings\ybai\My Documents\thesis
code\zhen0108.xls','Population');
INCOME=@ole('C:\Documents and Settings\ybai\My Documents\thesis code\zhen0108.xls','Income');
MINREQUIRED=780000;
MAXREQUIRED=783900;
INCOMELINE=2000;
PROFIT=180;
CASSAVABL=1000;
ENDDATA

[OBJ]Max = MaxPW(2);
MaxPW(1)=1;
!*****************************General Contraints*********************************************;
@FOR(DEMANDPOINTS(D):XCASSAVA(D)>=CASSAVABL*Y(D));
@FOR(DEMANDPOINTS(D):XCASSAVA(D)<=PRODUCTIONCAPACITY(D)*Y(D));
```

```
@SUM(DEMANDPOINTS(D):XCASSAVA(D))>=MINREQUIRED;
@SUM(DEMANDPOINTS(D):XCASSAVA(D))<=MAXREQUIRED;
@FOR(DEMANDPOINTS(D):L(D)=@IF(INCOME(D) #LE# INCOMELINE,1,0));
@FOR(DEMANDPOINTS(D):@BIN(Y(D)));
@FOR(DEMANDPOINTS(D):@BIN(L(D)));
!******************************1st objective*****************************************************;
MaxPW(1)=@SUM(DEMANDPOINTS(D):L(D)*Y(D)*POPULATION(D))/@SUM(DEMANDPOI
NTS(D):L(D)*POPULATION(D));
!******************************2nd objective*****************************************************;
@SUM(DEMANDPOINTS(D):TEMP2(D))=@SUM(DEMANDPOINTS(D):XCASSAVA(D)*L(D)*P
ROFIT);
@FOR(DEMANDPOINTS(D):TEMP2(D)>=MaxPW(2)*POPULATION(D)*INCOME(D)+BBB*Y(
D)*L(D)-BBB);
@FOR(DEMANDPOINTS(D):TEMP2(D)<=MaxPW(2)*POPULATION(D)*INCOME(D));
@FOR(DEMANDPOINTS(D):TEMP2(D)<=BBB*Y(D)*L(D));
@SUM(DEMANDPOINTS(D):L(D)*Y(D))>=1;
BBB=1000000000;
END
```

c. Minimize the distance objective function

```
MODEL:
SETS:
DEMANDPOINTS/1..70/:
XCASSAVA,INCOME,L,Y,PRODUCTIONCAPACITY,POPULATION,TEMP2,DisPD,T;
M/1,2/:MaxPW;
ENDSETS
DATA:
PRODUCTIONCAPACITY=@ole('C:\Documents and Settings\ybai\My Documents\thesis
code\zhen0108.xls','Production');
POPULATION=@ole('C:\Documents and Settings\ybai\My Documents\thesis
code\zhen0108.xls','Population');
INCOME=@ole('C:\Documents and Settings\ybai\My Documents\thesis code\zhen0108.xls','Income');
DisPD=@ole('C:\Documents and Settings\ybai\My Documents\thesis code\zhen0108.xls','DisPD');
@ole('C:\Documents and Settings\ybai\My Documents\thesis code\Jan22\step1.xls','Y')=Y;
MINREQUIRED=780000;
```

```
MAXREQUIRED=783900;
INCOMELINE=2000;
PROFIT=180;
CASSAVABL=1000;
ENDDATA

[OBJ]MIN = DISTANCE;
MaxPW(1)=1;
MaxPW(2)=0.119;
!********************************General Contraints*************************************************;
@FOR(DEMANDPOINTS(D):XCASSAVA(D)>=CASSAVABL*Y(D));
@FOR(DEMANDPOINTS(D):XCASSAVA(D)<=PRODUCTIONCAPACITY(D)*Y(D));
@SUM(DEMANDPOINTS(D):XCASSAVA(D))>=MINREQUIRED;
@SUM(DEMANDPOINTS(D):XCASSAVA(D))<=MAXREQUIRED;
@FOR(DEMANDPOINTS(D):L(D)=@IF(INCOME(D) #LE# INCOMELINE,1,0));
@FOR(DEMANDPOINTS(D):@BIN(Y(D)));
@FOR(DEMANDPOINTS(D):@BIN(L(D)));
!*********************************1st objective****************************************************;
MaxPW(1)=@SUM(DEMANDPOINTS(D):L(D)*Y(D)*POPULATION(D))/@SUM(DEMANDPOINTS(D):L(D)*POPULATION(D));
!********************************2nd objective*****************************************************;
@SUM(DEMANDPOINTS(D):TEMP2(D))=@SUM(DEMANDPOINTS(D):XCASSAVA(D)*L(D)*PROFIT);
@FOR(DEMANDPOINTS(D):TEMP2(D)>=MaxPW(2)*POPULATION(D)*INCOME(D)+BBB*Y(D)*L(D)-BBB);
@FOR(DEMANDPOINTS(D):TEMP2(D)<=MaxPW(2)*POPULATION(D)*INCOME(D));
@FOR(DEMANDPOINTS(D):TEMP2(D)<=BBB*Y(D)*L(D));
@SUM(DEMANDPOINTS(D):L(D)*Y(D))>=1;
BBB=100000000000;
!*******************************heuristic 3objective********************************************;
DISTANCE=@SUM(DEMANDPOINTS(D):DisPD(D)*T(D));
!T(D)=XCASSAVA(D)*Y(D);
@FOR(DEMANDPOINTS(D):T(D)>=XCASSAVA(D)+DDD*Y(D)-DDD);
@FOR(DEMANDPOINTS(D):T(D)<=XCASSAVA(D));
@FOR(DEMANDPOINTS(D):T(D)<=DDD*Y(D));
DDD=10000000;
```

```
!Data Output;
@SUM(DEMANDPOINTS(D):Y(D))=SUMY;
@SUM(DEMANDPOINTS(D):Y(D)*L(D))=SUMYL;
END
```

d. Minimize the 3rd objective

```
MODEL:
SETS:
DEMANDPOINTS/1..30/: XCASSAVA,INCOME,L,Y,
PRODUCTIONCAPACITY,POPULATION,TEMP2;
WAREHOUSE/1..30/: X,DisPW,Storage,Cost;
SELECTSET(WAREHOUSE,DEMANDPOINTS):Z,DisWD,XCASSAVAWD;
M/1,2/:MaxPW;
ENDSETS
DATA:
PRODUCTIONCAPACITY =@ole('C:\Documents and Settings\ybai\My Documents\thesis
code\Jan22\16\16-0.189.xls','Production');
POPULATION=@ole('C:\Documents and Settings\ybai\My Documents\thesis code\Jan22\16\16-
0.189.xls','Population');
INCOME=@ole('C:\Documents and Settings\ybai\My Documents\thesis code\Jan22\16\16-
0.189.xls','Income');
DisPW=@ole('C:\Documents and Settings\ybai\My Documents\thesis code\Jan22\16\16-
0.189.xls','DisPW');
DisWD=@ole('C:\Documents and Settings\ybai\My Documents\thesis code\Jan22\16\16-
0.189.xls','DisWD');
@ole('C:\Documents and Settings\ybai\My Documents\thesis code\Jan22\16\16-0.189.xls','Y')=Y;
@ole('C:\Documents and Settings\ybai\My Documents\thesis code\Jan22\16\16-0.189.xls','X')=X;
@ole('C:\Documents and Settings\ybai\My Documents\thesis code\Jan22\16\16-
0.189.xls','XCASSAVA')=XCASSAVA;
MINREQUIRED=780000;
MAXREQUIRED=783900;

INCOMELINE=2000;
PROFIT=180;
CASSAVABL=1000;
```

```
FixedCost=59000;
TCost=0.3;
Unit=0.1;
ENDDATA

[OBJ]MIN = SUMCOST;

MaxPW(2)>=0.190;
MaxPW(2)>=0.189;
@SUM(DEMANDPOINTS(D):Y(D)*L(D))=9;
!*************************************General Contraints*********************************************;
@FOR(DEMANDPOINTS(D):XCASSAVA(D)>=CASSAVABL*Y(D));
@FOR(DEMANDPOINTS(D):XCASSAVA(D)<= PRODUCTIONCAPACITY (D)*Y(D));
@SUM(DEMANDPOINTS(D):XCASSAVA(D))>=MINREQUIRED;
@SUM(DEMANDPOINTS(D):XCASSAVA(D))<=MAXREQUIRED;
@FOR(DEMANDPOINTS(D):L(D)=@IF(INCOME(D) #LE# INCOMELINE,1,0));
@FOR(DEMANDPOINTS(D):@BIN(Y(D)));
@FOR(DEMANDPOINTS(D):@BIN(L(D)));
!************************************2nd objective***************************************************;
@SUM(DEMANDPOINTS(D):TEMP2(D))=@SUM(DEMANDPOINTS(D):XCASSAVA(D)*L(D)*P
ROFIT);
@FOR(DEMANDPOINTS(D):TEMP2(D)>=MaxPW(2)*POPULATION(D)*INCOME(D)+BBB*Y(
D)*L(D)-BBB);
@FOR(DEMANDPOINTS(D):TEMP2(D)<=MaxPW(2)*POPULATION(D)*INCOME(D));
@FOR(DEMANDPOINTS(D):TEMP2(D)<=BBB*Y(D)*L(D));
@SUM(DEMANDPOINTS(D):L(D)*Y(D))>=1;
BBB=10000000000;
!************************************3rd objective***************************************************;
SUMCOST=@SUM(WAREHOUSE(W):COST(W));
@FOR(WAREHOUSE(W):COST(W)=FixedCost*X(W)+Unit*Storage(W)*0.75*0.3333
        +TCost*DisPW(W)*Storage(W)*0.25+TCost*DisPW(W)*Storage(W)*0.75*0.3333
        +TCost*DisPW(W)*Storage(W)*0.077
        +@SUM(DEMANDPOINTS(D):TCost*DisWD(W,D)*XCASSAVAWD(W,D))
        +@SUM(DEMANDPOINTS(D):TCost*DisWD(W,D)*XCASSAVAWD(W,D)*0.077));
@FOR(WAREHOUSE(W):Storage(W)=@SUM(DEMANDPOINTS(D):XCASSAVAWD(W,D)));
@FOR(SELECTSET(W,D):XCASSAVAWD(W,D)>=XCASSAVA(D)+DDD*Z(W,D)-DDD);
```

```
@FOR(SELECTSET(W,D):XCASSAVAWD(W,D)<=XCASSAVA(D));
@FOR(SELECTSET(W,D):XCASSAVAWD(W,D)<=DDD*Z(W,D));
DDD=1000000;

@FOR(DEMANDPOINTS(D):XCASSAVA(D)=@SUM(WAREHOUSE(W):XCASSAVAWD(W,D)));
@FOR(DEMANDPOINTS(D):Y(D)=@SUM(WAREHOUSE(W):Z(W,D)));
@FOR(DEMANDPOINTS(D):@SUM(WAREHOUSE(W):Z(W,D))<=1);
@FOR(WAREHOUSE(W):@FOR(DEMANDPOINTS(D):Z(W,D)<=X(W)));
@FOR(WAREHOUSE(W):@SUM(DEMANDPOINTS(D):Z(W,D))>=X(W));
@FOR(WAREHOUSE(W):@BIN(X(W)));
@FOR(SELECTSET(W,D):@BIN(Z(W,D)));

!Data Output;
@SUM(DEMANDPOINTS(D):Y(D))=SUMY;
@SUM(WAREHOUSE(W):X(W))=SUMX;
END
```

Appendix E

Part of C++ Code for Clark and Wright algorithm

```
// Algorithm.cpp: implementation of the Algorithm class.
//////////////////////////////////////////////////////////////////////
#include "stdafx.h"
#include "Algorithm.h"
//////////////////////////////////////////////////////////////////////
// Construction/Destruction
//////////////////////////////////////////////////////////////////////
Algorithm::Algorithm()
{
}
Algorithm::~Algorithm()
{
}
Algorithm::Algorithm(PointSet PSet)
{
        int i=0,j=0;
        InitPoints=PSet;
        for(int w=1;w<InitPoints.size();w++)
        {
                InitPoints[w].from=0;
                InitPoints[w].to=0;
        }
        TableSize=PSet.size();

        for(i=0;i<TableSize;i++)
        {
                for(j=0;j<TableSize;j++)
                {
                        Table[i][j].Bonus=0;
                        Table[i][j].Distance=0;
                        Table[i][j].x=0;
```

```
			}
		}
		for(i=0;i<TableSize;i++)
		{
			for(j=i+1;j<TableSize;j++)
			{
				if(i==0)
					Table[i][j].x=2;
				else
					Table[i][j].x=0;
				Table[i][j].Distance=InitPoints[i]-InitPoints[j];
				Table[i][j].Bonus=(InitPoints[i]-InitPoints[0])+(InitPoints[j]-InitPoints[0])-
(InitPoints[i]-InitPoints[j]);
			}
		}
}

Routs Algorithm::ClarkAndWright(double MaxDist)
{
	MaxDistance=MaxDist;
	CellIndex Index;
	Routs result;
	bool Cont=true;

	while(Cont)
	{
		switch(FindMaxBonus(Index))
		{
		case 0:
			Cont=false;
			break;
		case 1:
			Table[Index.x][Index.y].Bonus=0;
	if(InitPoints[Index.x].from==0 && InitPoints[Index.x].to!=0)
			{
				InitPoints[Index.x].from=Index.y;
```

```
				}else if(InitPoints[Index.x].from!=0 && InitPoints[Index.x].to==0)
				{
					InitPoints[Index.x].to=Index.y;
				}else{
	InitPoints[Index.x].to=Index.y;
				}
				if(InitPoints[Index.y].from==0 && InitPoints[Index.y].to!=0)
				{
					InitPoints[Index.y].from=Index.x;
				}else if(InitPoints[Index.y].from!=0 && InitPoints[Index.y].to==0)
				{
					InitPoints[Index.y].to=Index.x;
				}else{
	InitPoints[Index.y].from=Index.x;
				}
				break;
			}
		}
		CreateRouteSet(result);
		return result;
}

int Algorithm::FindMaxBonus(CellIndex &xx)
{
		int i=0,j=0,w=0;
		struct A
		{
			CellIndex index;
			double bonus;
		} x;
		xx.x=0;
		xx.y=0;
		x.index.x=0;
		x.index.y=0;
		x.bonus=0;
```

```
        for(i=1;i<TableSize;i++)
        {
                for(j=i+1;j<TableSize;j++)
                {
                        if(!(InitPoints[i].from!=0 && InitPoints[i].to!=0)
                                && !(InitPoints[j].from!=0 && InitPoints[j].to!=0))
                        {
                                if(!IsInSameRoute(i,j) && !IsExcessLimit(i,j))
                                {
                                        if(x.bonus<=Table[i][j].Bonus && Table[i][j].Bonus!=0)
                                        {
                                                x.index.x=i;
                                                x.index.y=j;
                                                x.bonus=Table[i][j].Bonus;
                                        }
                                }
                        }
                }
        }
        if(x.index.x==0 && x.index.y==0)
        {
                return 0;
        }else{
                xx.x=x.index.x;
                xx.y=x.index.y;
                return 1;
        }
}

bool Algorithm::IsExcessLimit(int p1,int p2)
{
        struct A
        {
                int from;
                int cur;
        } x;
```

```
 double dist=0;
 x.from=p1;
 if(InitPoints[p1].from!=0)
 {
         x.cur=InitPoints[p1].from;
 }else if(InitPoints[p1].to!=0)
 {
         x.cur=InitPoints[p1].to;
 }else{
         x.cur=0;
 }
 dist=(InitPoints[x.cur]-InitPoints[p1])+(InitPoints[p1]-InitPoints[p2]);

 while(x.cur!=0)
 {
         if(InitPoints[x.cur].from!=x.from)
         {
                 dist=dist+(InitPoints[x.cur]-InitPoints[InitPoints[x.cur].from]);
                 x.from=x.cur;
                 x.cur=InitPoints[x.cur].from;
         }else{
                 dist=dist+(InitPoints[x.cur]-InitPoints[InitPoints[x.cur].to]);
                 x.from=x.cur;
                 x.cur=InitPoints[x.cur].to;
         }
 }
 x.from=p2;
 if(InitPoints[p2].from!=0)
 {
         x.cur=InitPoints[p2].from;
 }else if(InitPoints[p2].to!=0)
 {
         x.cur=InitPoints[p2].to;
 }else{
         x.cur=0;
 }
```

```
		dist=dist+(InitPoints[x.cur]-InitPoints[p2]);

		while(x.cur!=0)
		{
			if(InitPoints[x.cur].from!=x.from)
			{
				dist=dist+(InitPoints[x.cur]-InitPoints[InitPoints[x.cur].from]);
				x.from=x.cur;
				x.cur=InitPoints[x.cur].from;
			}else{
				dist=dist+(InitPoints[x.cur]-InitPoints[InitPoints[x.cur].to]);
				x.from=x.cur;
				x.cur=InitPoints[x.cur].to;
			}
		}

		if(dist>MaxDistance)
		{
			return true;
		}else{
			return false;
		}
}

bool Algorithm::IsInSameRoute(int p1,int p2)
{
		struct A
		{
			int from;
			int cur;
		} x;
		x.from=p1;
		if(InitPoints[p1].from!=0)
		{
			x.cur=InitPoints[p1].from;
		}else if(InitPoints[p1].to!=0)
```

```
		{
			x.cur=InitPoints[p1].to;
		}else{
			return false;
		}
		while(x.cur!=0)
		{
			if(x.cur==p2)
				return true;
			if(InitPoints[x.cur].from!=x.from)
			{
				x.from=x.cur;
				x.cur=InitPoints[x.cur].from;
			}else{
				x.from=x.cur;
				x.cur=InitPoints[x.cur].to;
			}
		}
		return false;
}

void Algorithm::CreateRouteSet(Routs &RouteSet)
		{
		Route X;
		for(int i=1;i<InitPoints.size();i++)
			{
			if(InitPoints[i].from==0 || InitPoints[i].to==0)
				{
	X=CreateRoute(i);
				RouteSet.Add(X);
	InitPoints[i].from=-1;
				InitPoints[i].to=-1;
				}
			}
		}
```

```
Route Algorithm::CreateRoute(int StartID)
        {
        Route R;
        R.Add(InitPoints[StartID]);

        struct A
                {
    int from;
                int cur;
                } x;

  x.from=StartID;
        if(InitPoints[StartID].from!=0)
                {
                x.cur=InitPoints[StartID].from;
                }else if(InitPoints[StartID].to!=0)
                {
                x.cur=InitPoints[StartID].to;
                }else{
      return R;
                        }
        while(x.cur!=0)
                {
                R.Add(InitPoints[x.cur]);
                if(InitPoints[x.cur].from!=x.from)
                        {
                        x.from=x.cur;
                        x.cur=InitPoints[x.cur].from;
                        }else{
                                x.from=x.cur;
                                x.cur=InitPoints[x.cur].to;
                                }
                }
      InitPoints[x.from].from=-1;
      InitPoints[x.from].to=-1;
return R;}
```