# Design, Simulation, Analysis and Optimization of Transportation System for a Biomass to Ethanol Conversion Plant

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ABSTRACT

The US Department of Energy has set an ambitious goal of replacing 30% of current petroleum consumption with biomass and its products by the year 2030. To achieve this goal, various systems capable of handling biomass at this magnitude have to be designed and built. The transportation system for a cotton gin was studied and modeled with the current management policy (FIFO) used by the gin to gain understanding of a logistic system where the processing plant (gin) pays for the transportation of the feedstock. Alternate management policies for transporting cotton modules showed significant time savings of 24% in days-to-haul.

To design a logistics system and management strategy that will minimize the cost of biomass delivery (round bales of switchgrass), a seven-county region in southern Piedmont region of Virginia was selected as the location for a 50 Mg/h bioprocessing plant which operates 24 h/day, 7 days/week. Some of the equipment are not be commercially available and need to be developed. The transport equipment (trucks, loaders and unloaders) was defined and the operational parameters estimated. One hundred and fifty-five secondary storage locations (SSLs) along with a 3.2-km procurement area for each SSL were determined for the region. The travel time from each SSL to the plant was calculated based on a network flow analysis.

Seven different policies (strategies) for scheduling loaders were studied. The two key variables were maximum number of trucks required and the maximum at-plant inventory. Five policies were based on “Shortest Travel Time - Longest Travel Time” allocation and two policies were based on “Sector-based” allocation. Policies generating schedules with minimum truck requirement and at-plant storage were simulated. A discrete event simulation model for the logistic system was constructed and the productive operating times for system equipment and inventory was computed. Lowest delivered cost was \$14.68/Mg with truck cost averaging \$8.44/Mg and loader cost averaging \$2.98/Mg. The at-plant inventory levels were held to a maximum of 390 loads. The loaders operated less than 9,500 hours and the unloaders operated for a total of 2,700 hours for both systems simulated.

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# Chapter 1 – Introduction

## *1.1 Background / Motivation*

United States economy depends on continuous availability low cost energy. This dependence on lower cost energy has assumed increased significance in the current economic and political scenario. More than 85% of energy consumed in year 2005 in United States was from fossil fuels, namely coal, petroleum, and natural gas. Less than 7% of energy was from renewable resources, of which, alcohol fuels was a mere 0.4% (Department of Energy, 2006).

This widespread use of fossil fuels and the resulting release of fossilized carbon dioxide and other green house gasses have been blamed for global warming, increasing sea levels and changing climatic patterns. This has led to a renewed global interest in fuels from biological sources; as they are usually net zero contributors to greenhouse gasses.

The Department of Energy's Biomass research and development Committee is the premier organization in this field. They have set an ambitious goal of replacing 30% of current petroleum consumption by biomass and its products by the year 2030 (Department of Energy, 2003). To achieve this goal, various systems capable of handling biomass at this magnitude have to be designed and built.

Currently, there are no facilities, or formalized plans, available to move massive amounts of biomass from a procurement area that will sufficiently supply large processing plants for continuous operation. Due to the complex nature and expense of building such a system, this study was initiated. A review of literature revealed that no system of raw material delivery currently exists like the one proposed for this study. The closest system was the system for delivery of seed cotton to a gin. Thus, the logistics system of a gin in Emporia, Virginia was studied to understand basic operating parameters and how (if) these parameters might be applied for a biomass logistics system.

There is a need for a process to assemble a state-of-the-art logistic system and management policies that will deliver the raw material needed for a processing plant to meet a weekly demand. The cotton gin in Virginia operates 90 days per year and a sugar mill in Florida operates 140 days per year. No commercial plant in Southeastern U.S. operates 350 days per year using a herbaceous feedstock. Some of the components of such a system are not commercially available and need to be developed. These components (equipment) will be defined and the operational parameters estimated.

A specific database was developed for this study. It was used to evaluate several scheduling policies. The best two policies were simulated using a discrete event simulation model. The simulation produced productivity factors for the various equipment used in this study (trucks, loaders, and unloaders). The use of this specific study's analysis, although restricted in scope, provides a framework for evaluating future development and identifying critical areas that need to be addressed before commercial success can be assured. With a focused study, different component designs can be evaluated, the performance of the system responses can be observed and economic impact assessed. The response to operational characteristics of the system can be observed, cost estimated can be evaluated when using different management policies. Finally, by relaxing operational constraints, the system's response can be characterized and management factors prioritized.

Though this dissertation is devoted to a single specific study, the framework and the concepts developed should be transferable to any location and readapted for newer equipment and management policies.

## *1.2 Research Objectives*

The overall goal of this research is to design a logistics system and management strategies that will minimize the cost of biomass delivery from a procurement area to a bioprocessing plant. This research will

1. Define the interacting components and operational parameters used in the logistic system
2. Determine optimal plant location based on road travel times in a procurement region.
3. Determine the best management policies for scheduling loaders to SSLs to satisfy weekly raw material demand by the plant.
4. Determine operational characteristics of the logistic system using a discrete event simulation model and two of the best scheduling policies.
5. Determine the sensitivity of the logistic system to truck travel times, plant processing times and land use rate.

## *1.3 Organization of this dissertation*

The dissertation is divided into several chapters that build the logistical system and define the management strategies to be studied. Chapter 2 defines the case study that establishes a bioprocessing plant that runs continuously for 24 h/day, 7 day/wk for 50 wk/yr at a capacity of 50 Mg/h. Biomass requirements were established and a transport system was defined. Equipment components were described for both harvest and handling of biomass in the proposed system. The interactions of these components with other subsystems were discussed. The defined transportation system has several components that are not commercially available and proposed equipment and operational parameters for these components were estimated.

Chapter 3 provides a review of literature relevant to this study, beginning with the need for a biomass energy system. It looks at various biomass (switchgrass) system studies in the US and rest of the world. Biomass facility location studies and its solution techniques are along with a literature review of biomass logistics and biomass simulation are presented. Literature on traveling salesman problem (TSP) and vehicle routing problem along with their solution techniques are also presented.

To better understand the operational characteristics of hauling biomass on road, a database with truck travel times and module call in times was obtained from the Mid

Atlantic Gin, Emporia, Virginia. A study of the cotton gin's transportation systems (Chapter 4) was investigated to evaluate the complex interrelationships and to define transport operational parameters. The current management policies and proposed methods for transporting cotton module were evaluated and compared using discrete event simulation and optimization techniques.

Chapter 5 describes a technique for locating a bioprocessing plant in two Piedmont regions, classified as "Northern Piedmont" and "Southern Piedmont" in Virginia. A process was demonstrated to identify the biomass resources within these regions and define gathering points (Secondary Storage Locations or SSLs) within a 3.2 km (2 mile) radius procurement region around each SSL. Spatial solution techniques were used to locate the optimal location of the plant. The constraints of the procurement area were the percentage of existing pasture land that would be allocated for growing feedstock. The average yield was assumed constant in the production region. The amount of material stored at the SSLs, travel time for the truck transport from each SSL, and the number of SSLs required were documented. The dataset for the southern region was used for scheduling analysis.

Following the establishment of the plant and SSL locations, seven management strategies (Chapter 6) were investigated to demonstrate the operational characteristics of moving massive amounts of biomass to a processing plant. These management strategies were evaluated based on reducing total delivery cost, which meant minimizing the amount of at-plant inventory and the maximum number of trucks needed. From these analyses, two management strategies were selected which appeared to have the best features and modeled using a discrete event simulation.

Chapter 7 describes the development of a simulation and shows the simulated results. Using operational parameters of the two strategies simulated, an economic analysis of these strategies were developed and studied. Chapter 8 is a summary of the lessons learned from the study of the cotton gin and the simulation of the two management strategies for the logistical system for the bioprocessing plant. The conclusions are stated as a set of rules that can be used to minimize delivered cost. Extensions and modifications to the model are also presented.

# Chapter 2 – Problem Definition and System Description

## *2.1 Biomass to Ethanol Industry*

The fuel ethanol industry is well established in the US. Plants that convert corn into ethanol currently consume 6% of annual corn production, and produce 5.6 billion liters (1.5 billion gallons) of fuel ethanol per year (Sokhansanj et al., 2002). To put this number into perspective, 5.6 billion liters is 0.5 % of total fuel consumed by transport sector in the year 2002 (Department of Energy, 2006b). This low level of renewable energy usage has to be increased significantly to improve the quality of life and preserve the environment.

Just as there is a cost to extract crude oil from the Earth, there is also a cost to extract (produce, harvest and deliver) biomass from fields. Currently, the cost to extract biomass and convert it to a usable energy source is much higher than that of fossil fuels. It is expected that by designing an efficient biomass production/delivery system, this price difference will be minimized. It is expected that unless the world crude production is significantly reduced, petroleum will continue to be cheaper than other competing products due to its established infrastructure and energy density per liter of raw crude when compared with biomass. But, there will be a large pool of environmentally conscious or politically active people/populace that will pay a premium for biofuels or other environmentally safer fuels (Roe et al., 2001).

There have been an increasing number of organizations that use green power co-firing plants, wind/water generator and biomass powered electric plants extensively. They advertise as such to show that they are environmentally responsible. One such organization is Toyota Motor Corporation in the US (Department of Energy, 2007). It is expected that the number of industries using biomass/bioenergy will continue to grow.

## *2.2 Design – Problem definition:*

Two separate production regions in the Piedmont region of Virginia were considered for this study. One production region was located in Southern Piedmont region of Virginia (henceforth referred to as SPV) and consisted of Henry, Franklin, Pittysylvania, Halifax, Bedford, Charlotte and Campbell counties. The other production region was located in Northern Piedmont region of Virginia (henceforth referred to as NPV) and consisted of Madison, Orange, Albermarle, Spotsylvania, Fluvanna, Greene, and Louisa counties. Figure 2.1 shows these two production regions.

These countries were well known for their tobacco production. Given the prevailing public perception on smoking, the number of farms that are in tobacco production is declining. The resulting decrease in economic activity and lack of wealth generation has created an economic slump in these counties. This has led to a large migration of workforce to other regions, causing a further decline in economic activity. This aging of population also prevents other types of economic activity to flourish in this region. Various programs are in place to assist this region to grow economically. By constructing a conversion plant in this region, the "value" of return from hay production could grow and improve the local economy.

The counties listed in Table 2.1 and Table 2.2 has some of the largest hay producing regions in Virginia and were selected based on that attribute. The availability of a large number of hay fields will help the transport system for the proposed biomass plant achieve lower cost due to reduced transport cost per unit of feedstock delivered. A high concentration of production fields within a given radius of the plant reduces the average transportation cost per unit of the feedstock.

**Table 2.1 Five year average yield in Northern Piedmont, Virginia (NPV)**

| County | Hay (ha) | Hay yield (Mg/ha) | Alfalfa (Mg) | Alfalfa yield (Mg/ha) |
|---|---|---|---|---|
| Henry | 3,358.89 | 3.50 | 453.59 | 4.48 |
| Franklin | 11,679.23 | 4.39 | 1,542.21 | 6.99 |
| Pittysylvania | 14,771.02 | 4.08 | 1,669.22 | 5.65 |
| Halifax | 8,757.40 | 3.99 | 997.90 | 6.99 |
| Bedford | 20,460.90 | 3.90 | 2,286.11 | 5.87 |
| Charlotte | 6,110.75 | 3.63 | 780.18 | 5.51 |
| Campbell | 10,189.98 | 3.68 | 925.33 | 5.92 |

**Table 2.2 Year average yield in Southern Piedmont, Virginia (SPV)**

| County | Hay (ha) | Hay yield (Mg/ha) | Alfalfa (Mg) | Alfalfa yield (Mg/ha) |
|---|---|---|---|---|
| Madison | 7,939.93 | 4.98 | 997.90 | 7.08 |
| Orange | 9,429.17 | 4.17 | 979.76 | 7.08 |
| Albemarle | 12,626.19 | 3.72 | 1,487.78 | 6.28 |
| Spotsylvania | 4,224.92 | 4.71 | 544.31 | 6.41 |
| Fluvanna | 5,560.38 | 3.32 | 566.99 | 5.60 |
| Greene | 2,921.83 | 4.30 | 453.59 | 4.26 |
| Louisa | 7,616.18 | 4.08 | 1,850.66 | 5.96 |

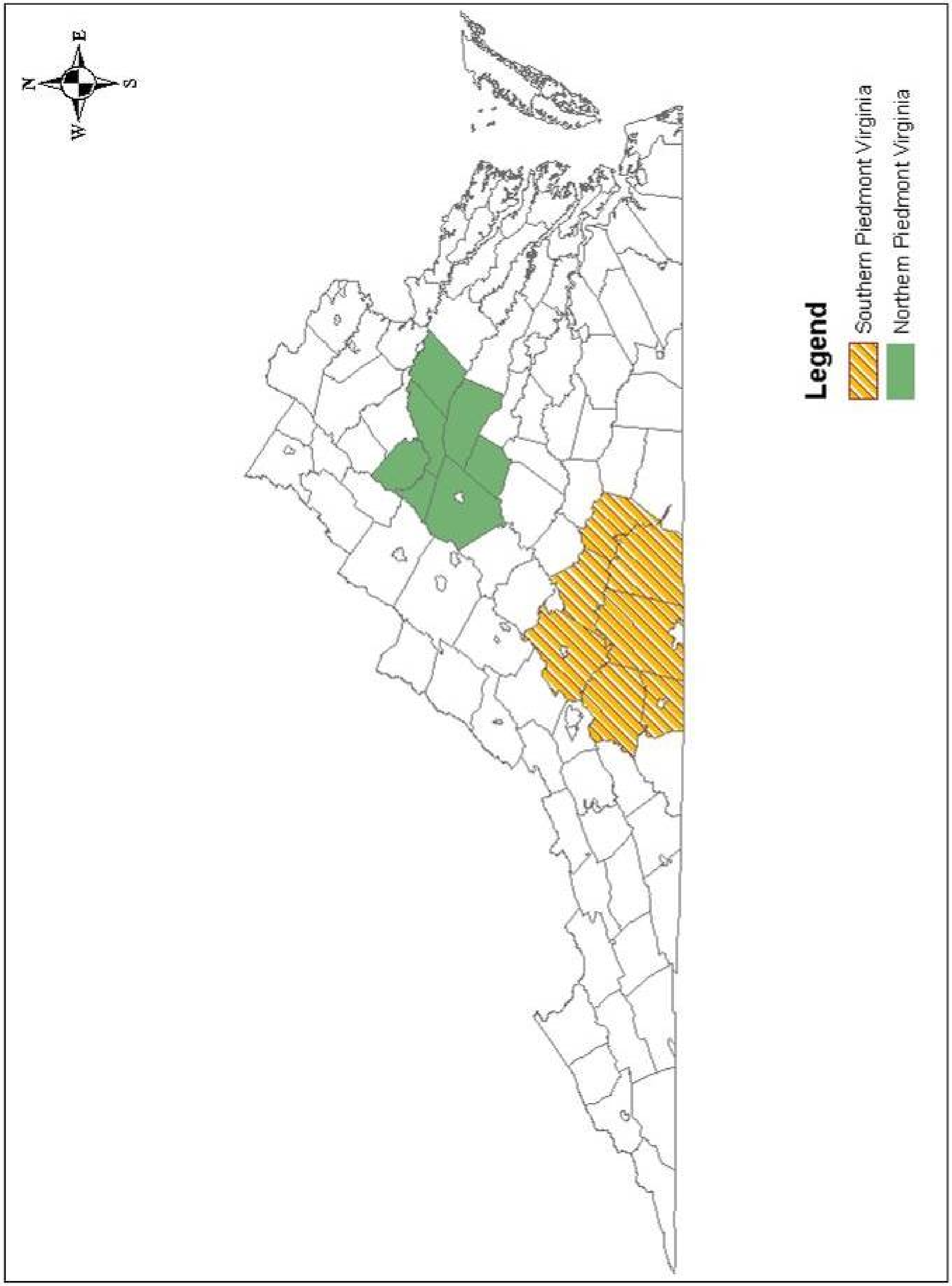


**Figure 2.1 Northern Piedmont, Virginia and Southern Piedmont, Virginia regions selected for the study**

## *2.3 Systems definitions/ descriptions*

The transport system in this study starts with flow of biomass in the form of round bales (diameter = 1.5 m, length = 1.2 m) into Secondary Storage Locations (SSLs, refer to section 2.3.2). These bales are stored in ambient storage, on a crushed rock surface. Loaders (refer to section 2.3.4) load these stored bales into trucks and these trucks transport the bales to a processing plant. A gantry crane or a counter balanced truck unloads these bales and supplies the plant with needed material. Figure 2.2 describes this system as "seen" by a biomass bale moving through the system. The reminder of this section describes in detail the specialized non-commercial machinery used in this logistical system's operation, along with terminology used in this dissertation.

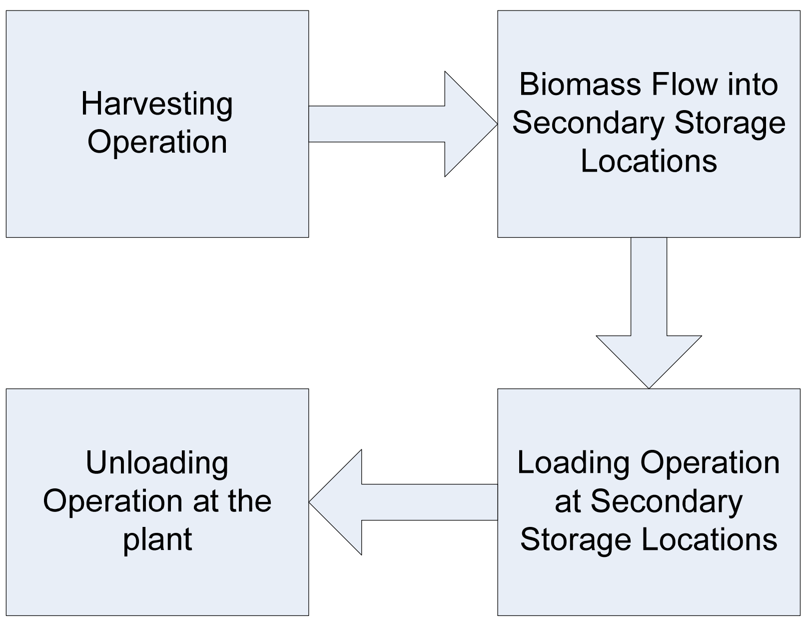


**Figure 2.2 Operational Flowchart for biomass flow**

### *2.3.1 Bale wagon*

A bale wagon is a self propelled machine that self loads round bales. It was first constructed in 1980s by New Holland to transport hay bales efficiently from their drop location on fields to their storage location (Priepke, 2007). This machine has the ability to travel on fields with minimal damage to the soil and can also travel on roadways while transporting eight bales at a time. It can load and unload bales without the need for additional support machinery or operators. This ability is crucial when short cycle times are needed.

Since the bale wagon’s maximum on-road speed is less than 32 km/h (20 mph), its radius of operation needs to be limited to avoid large travel times per cycle between the field and SSL. In this study, a bale wagon’s operational radius was limited to 3.2 km (2 miles). It unloads the bales by tilting the bed and allowing the bales to roll onto the ground. The goal is to align the bales into a neat grid as shown in Figure 2.3.

### *2.3.2 Secondary storage locations or SSLs*

On-road trucks are trucks that normally travel on interstates and other paved roads. These trucks cannot traverse into a field to pickup bales, as they will loose traction and damage the field. Since there has to be a transition between in-field hauling and over-the-road hauling, it is logical to do this at the SSL. The SSL will have a Department of Transportation approved entrance onto a state maintained road. It will have a gravel surface suitable for loader and truck operation year-around. It is assumed that a SSL can be loaded or unloaded at any time during the year.

To keep total system cost low, each SSL will take in bales from its surrounding area. This allows a SSL’s facility cost to be spread over a larger production area and also reduces the number of SSLs in the system. Reducing the total number of SSLs in this system translates to lesser travel time between SSLs for a loader crew and a higher number of loads per SSL. For the purpose of this study, the production area is restricted to a 3.2 km (2-mile) radius from a SSL. In reality, such a location might receive bales from locations outside its service area. Such cases were not explored in this model. Net-wrapped round bales are stored in ambient conditions till they are transported to the processing plant. The SSL concept is analogous to the “wood yards” used for short term storage by the forest industry (Figure 2.4).

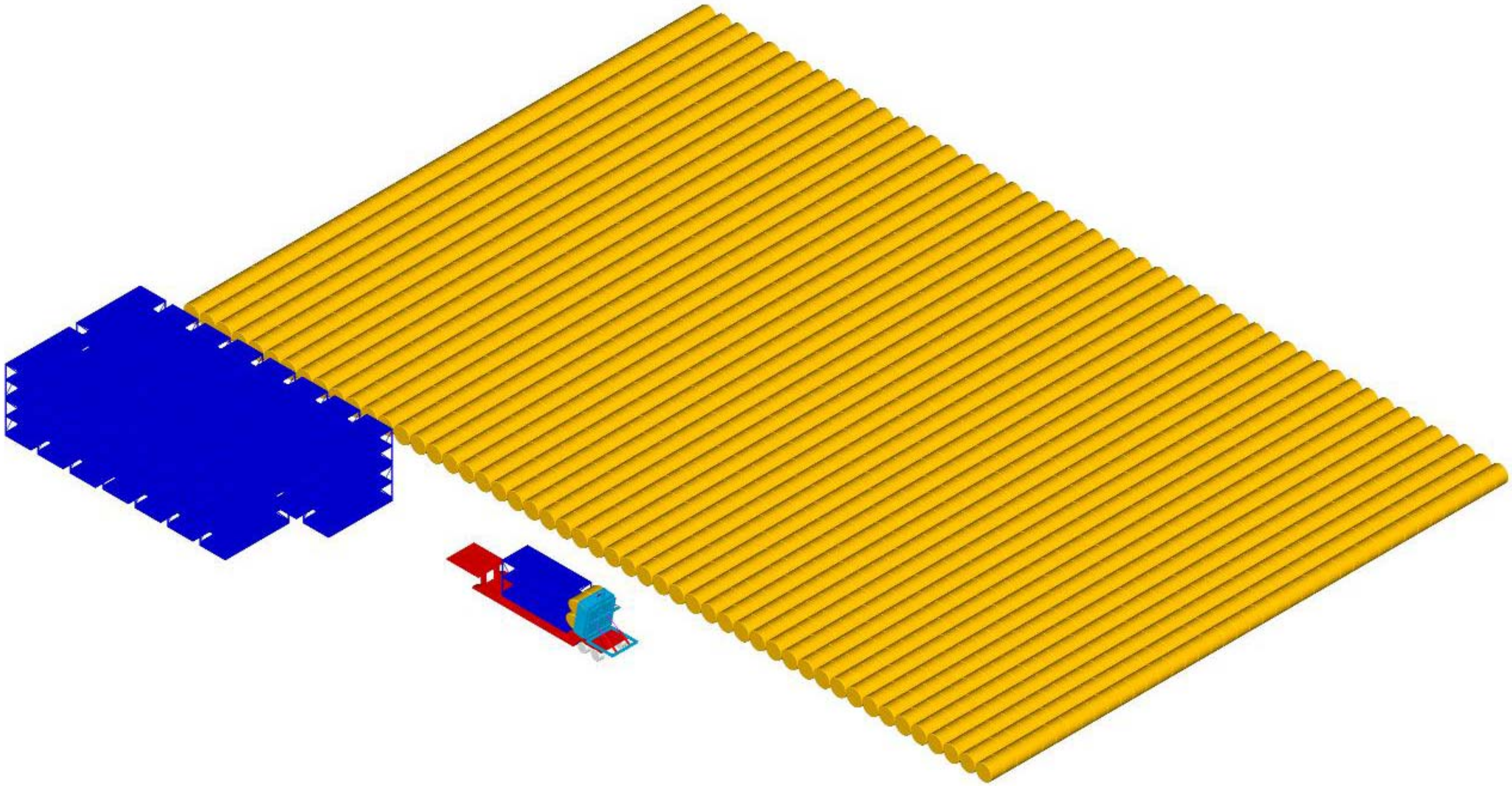

**Figure 2.3 Single layer ambient storage of round bales in SSL. View shows 1920 bales.**


**Figure 2.4 An example of crushed rock surface at a wood yard in Pittsylvania County, Virginia**

### 2.3.3 Processing plant

The bales of biomass delivered to the processing plant are wrapped with plastic net and consists of two separate layers: the outer layer, called the weathered layer and the inner layer called core. The weathered layer, may be of lesser value to some bioenergy products, therefore it needs to be separated from the core. Separating these two grades of raw materials will enable the processing plant to use two different processes to process these distinct layers efficiently. Figure 2.5 shows a string wrapped hay bale. The outer weathered layer can be clearly observed.

The weathered outer layer may be used as a feedstock for a biomass/municipal solid waste electricity generation plant. Power from this plant can be used to process inner core of these round bales and process them into a more energy dense material. Excess electricity may also be sold to the electric grid to power other green-power based industries. For this analysis, the effects of this weathered layer were ignored.


**Figure 2.5 An example of weathered layer on a round bale in single layer ambient storage**

It is expected that the next step in this conversion process will be performed at a larger, specialized facility that processes raw material from several sources. This requirement means that the processing plant should have ready access to rail lines, as the processing plant is expected to use rail transport, due to its inherent lower cost. The details of downstream operations of the processing plant are beyond the scope of this study.

The processing plant will be operating 24 hours-a-day, 7 days-a-week and 50 weeks-per-year and the goal is for continuous operation. This study presumes that the plant capacity is 50 Mg/h. The receiving facility for the plant will begin operation at 0630 h every week day and stop at 1830 h (12 hours per day) at the receiving facility. This asymmetry between load/unload operations at the SSLs and the processing plant operation forces the processing plant to invest in an on-site storage, capable of storing excess material during normal unload operations and supply the plant with stored material during periods with zero material inflow. This onsite storage location will have a capability to supply biomass from 1830 h to 0630 h every week day and from 1830 h Friday to 0630 h Monday during weekends.

### 2.3.4 Loader at SSL

The round bales, stored in ambient conditions in the SSL, need to be loaded onto a tractor trailer truck to be moved or transported to the preprocessing plant. Specialized equipment for loading these trucks is under development/construction at Virginia Tech. Only the operational parameters for loading and its estimated purchase cost were used in this analysis due to an existing confidentiality agreement. It is expected that the loader can fully load a truck (32 bales) in less than 30 minutes. Figure 2.6 shows the loading operation at a SSL with a frame loader. It is important to note that the grid arrangement of bales is an essential requirement for the loader to achieve efficient cycle times.

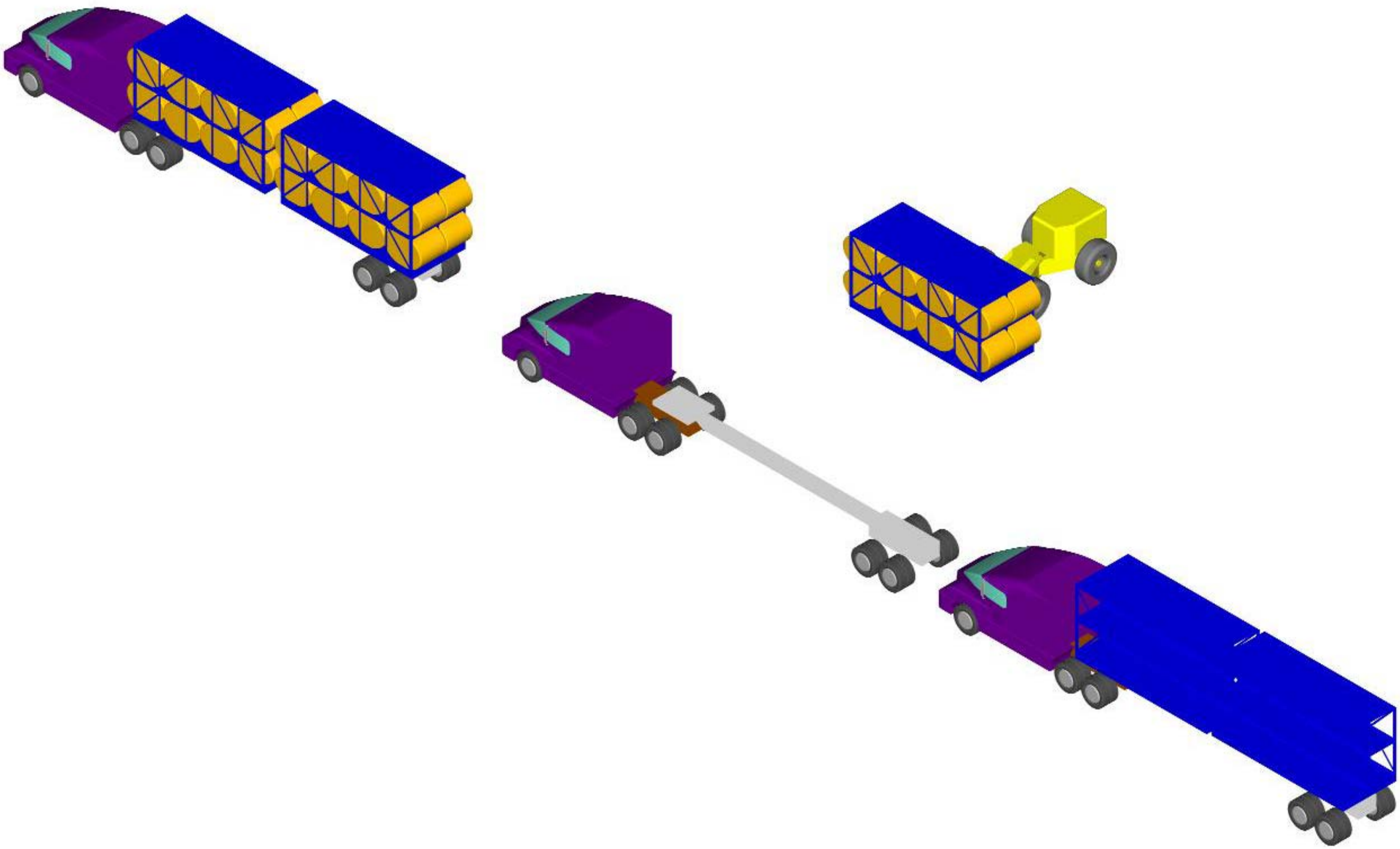

**Figure 2.6 Frame being loaded with round bales at a SSL.**

### 2.3.5 Detachable frame trucks

This term refers to specially modified on-road trailers that can detach its frame similar to a shipping container. The frame is specially designed for easy attach/ detach operations and unloading the bales from the frame. These frames will also serve as temporary storage modules at the receiving facility. These frames are unloaded into a storage area at the plant. The frames are double stacked in the storage area to reduce the inventory footprint. Figure 2.7 shows full frames from trucks being unloaded on one side and empty frames loaded on to the trucks on the other.

### 2.3.6 Truck Based Unload System

Specialized trucks, which can self unload by moving its trailer bed, are commercially available and are called walking floor trailers due to their movement mimicking a walking motion (Moser, 1994). It is expected that for a smaller biomass processing plants, a setup using these trucks will reduce high initial cost associated with rail based systems. The major drawbacks of this system include significant time loss due to increased unloading time and higher initial investment cost.

### 2.3.7 Rail based System

In a rail based facility, detachable frame trailers are used to transport bales from SSLs to a processing plant. A fully loaded truck enters the facility and gets weighed-in at the truck scale. A traveling boom container crane (or a gantry crane) lifts the loaded frame and places it on a rail car. Each rail car can have up to four truck frames, in two stacks. The empty truck (without its frame) then move to the other side of the crane or move on to another gantry of similar or lesser capacity. This crane will place an empty frame on the truck. This empty truck will again be weighed before it returns to the field.

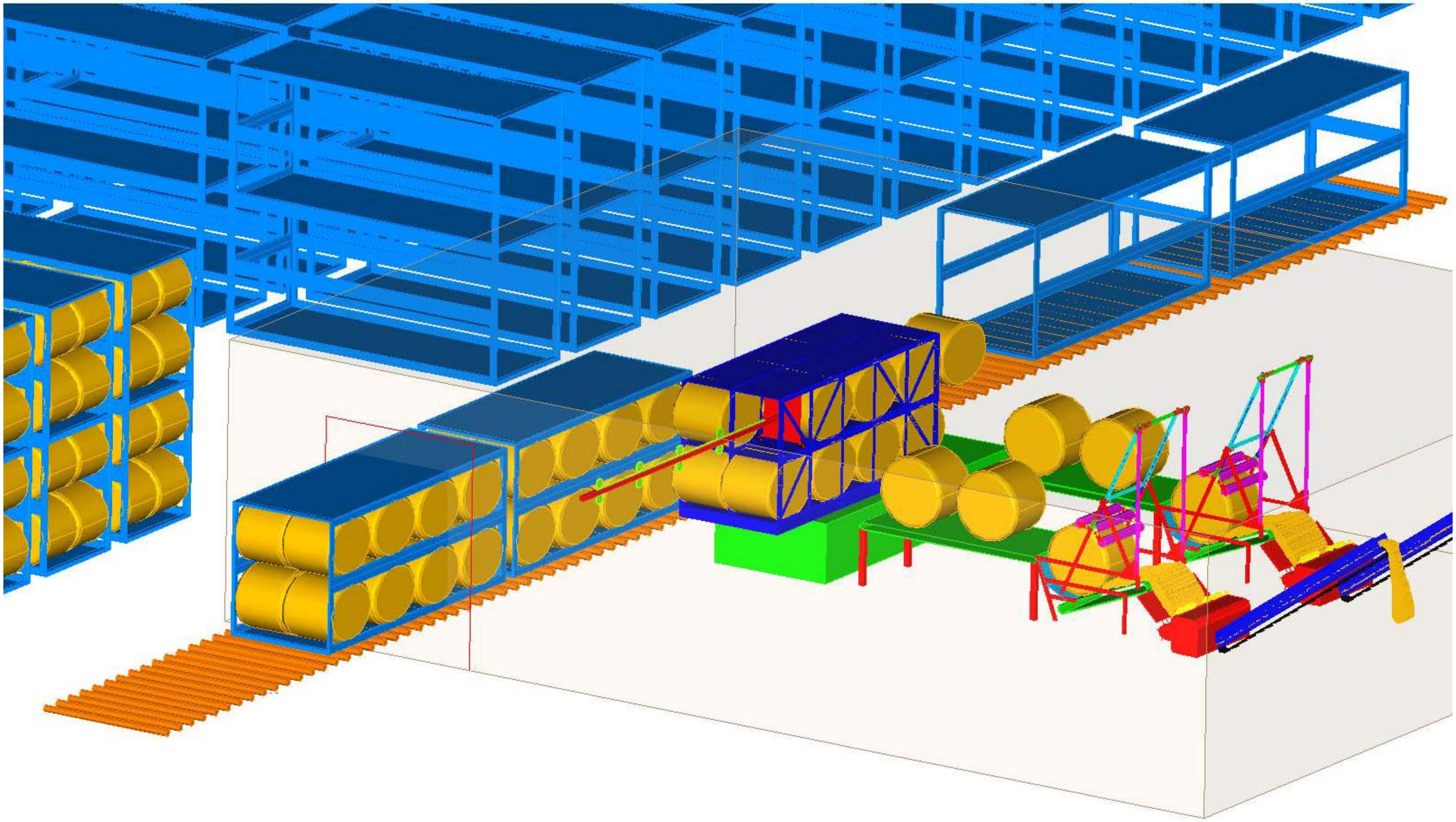

**Figure 2.7 Loaded frames being conveyed into pre-processing plant where individual bales are removed for processing.**

The rail cars act as temporary on-site storage location for the processing plant and supply it with biomass from 1830 h to 0630 h every week day and from 1830 h Friday to 0630 h Monday during weekends. The significant drawbacks to this system are its high initial investment on machinery and infrastructure.

## 2.4 System Interaction

To better understand the systems under consideration, the biomass bale at the field, after it is ejected from a baler, will be examined. The bale is picked up by a bale wagon along with nine other bales. The bale wagon will move on a field, farm (unpaved) road and some combination of primary, secondary and tertiary roads to reach a SSL less than 3.2 km (2 miles, Euclidian) from the field. The bale wagon places these bales in a neat horizontal manner as required by the loader. This operation will be repeated at all the other SSLs through out the harvesting season. The processing plant schedules a loader to visit a SSL based on the management policy followed. The loader picks up four bales at a time and loads them into a frame. The loader performs this operation seven more times on the same truck, taking 30 min for a truck. The loader then repeats this process on the next truck. The fully loaded truck then travels on a combination of primary, secondary and tertiary roads to reach the processing plant.

If the processing plant has a rail based system, the entire truck frame is picked up by the Gantry and placed on a rail car. The gantry will place another frame on top of the first one. Two stacks of two frames per stack can be placed per rail car. Depending on the demand, rail cars will move into its unloading dock and dump its bales for processing. This describes the life cycle of a biomass bale from baler to processing plant.

If the conversion plant has a truck based system, then the truck moves into one of the many unloading rows and activates its walking floor. This unloads all 32 bales into this row. A front end loader then pushes these bales, as needed, into a powered conveyor that dumps these bales into the plant for processing.

## 2.5 Summary:

The following constraints were defined for the system in this study.

1. Each loader will operate 10 h/day. Each load operation takes 30 min and a loader can load a maximum of 15 loads per day.
2. The loader will always have a truck available for loading.
3. Each truck can operate 10 h/day.
4. The trucks wait for the loaders to become available.
5. The maximum number of trucks used in the system should be minimized.
6. The plant location in the system should be placed such that the total number of trucks is minimized.
7. The plant should never run out of feedstock.
8. The plant consumes 50 Mg/h, which translates to 3.5 loads/h. Each load contains 14.4 Mg of feedstock
9. Each SSL should be completely exhausted before the loader can move to the next SSL.

# Chapter 3 – Literature Review

“America’s oil dependence threatens our national security, economy and environment” – (Greene, 2004).

United States needs cheap energy to continue to grow. Energy and energy security has long been a major concern. With economies of countries like China and India growing at sustained rates of around 7 to 8% per year, demand for oil and other energy sources will only go up, driving prices higher and potentially triggering a global recession or slowing down current recovery.

With little less than 3% of known oil reserves, United States currently consumes 25% of world crude production (Greene, 2004). Of this, 27% is consumed by the transportation sector (Department of Energy, 2006). Switching to an alternate source of energy in this sector will be the most beneficial as other sectors, due to their larger size and fixed locations can use better pollution control equipment to reduce harmful emissions. Ethanol, bio-diesel and similar liquid fuels that can use existing technology and distribution infrastructure in this sector will have the best short and medium term impact. Zero emission devices, like fuel cells, are not expected to be commercially viable for another 10 to 15 years. Not only will such a move towards bioenergy reduce greenhouse emissions, it may also reduce soil erosion and improve wild life by recapturing dormant fields into productive agricultural use. This will also help with the balance of payment/trade deficit and provide alternate crops for US farmers. Hopefully, these new crops will produce additional income that can improve rural economies.

## *3.1 Production of Herbaceous Biomass:*

To this end, Oak Ridge National Lab’s (ORNL) Biomass Feedstock Development Progress (BFDP) was tasked with identifying and evaluating different biomass as an alternate source of energy (Ferrell et al., 1995). Of more than 30 herbaceous crops species that were evaluated during 1980s, BFDP decided to focus on a high yielding perennial grass species, switchgrass, due to its excellent conservation characteristics and compatibility with existing farming practices (McLaughlin et al., 1999; McLaughlin, 1992). Switchgrass, as observed by Greene (2004), can be used to produce ethanol. Residue from this process includes lignin, which can be gasified to produce synthesis gas or Syngas. Syngas can be further used to produce dimethyl ether and Fischer Tropsch fuels with appropriate catalysts. Green also notes that lignin residue, after ethanol extraction, has enough energy left to power the entire conversion process and produce fuel and power for supply to local customers.

Dias (1995) stated that cool season grasses in Virginia have an average yield of 3.5–5.5 Mg/ha. Yields as high as 6.0 Mg/ha can be achieved in central Virginia. (Parrish et al., 1993) reported switchgrass yielded 13 Mg/ha in research plots in Blacksburg, VA. Sladden et al.,(1991) reported yields of 34.6 Mg/ha in Alabama. Greene (2004) noted that using current switchgrass varieties and agronomic practices, an annual yield of 11.20 dry Mg/ha (5 dry tons/acre) per year can be expected.

Dias (1995) further noted that single cutting yielded (in Blacksburg) 13.4 Mg/ha, while double-cutting yielded 13.7 Mg/ha and 4.1 Mg/ha respectively, giving an annual total of 17.8 Mg/ha. Cultivar NC-2's yields were 10.9 Mg/ha, 11.7 Mg/ha and 5.8 Mg/ha respectively.

Given such a significant difference in yield, both single and double cutting strategies are expected in viable commercial systems. For the purpose of this study, 9 Mg/ha was assumed. This was an average yield across the entire production area. It was understood that fields with better soil and good management will produce yields approaching 13 Mg/ha found in research plot.

### *3.2 Harvesting of Herbaceous Biomass:*

Cundiff and Marsh (1996) studied harvest and storage of large round (1.8 m diameter, 1.5m wide) and large square bales (1.2 m high, 1.2 m wide, 2.4 m long). They noted that when harvesting a field yielding 9 Mg/ha (dry), it costs $12.25/Mg (dry) to bale large square bales, while it costs $15.90/Mg (dry) to bale large round bales. Square bales, due to their tendency to catch fire spontaneously when wet or rained on, needed to be stored in covered storage or protected using plastic covers. This additional storage cost pushed its final cost estimates to $27 per dry Mg. In contrast, round bales with their thatched roof property allowed them to be stored in ambient storage. Round bales stored in such a fashion cost $20/Mg (dry). Burnback et al. (1995) noted that storing such round bales over a period of 12 months did not affect the composition in mature switchgrass (Cave-N-Rock variety). This difference in cost between square bales and round bales dictated the use of round bales in this analysis.

### *3.3 Proposed Operation of a Preprocessing plant:*

Cundiff et al. (2004) proposed a plan for operating a processing plant 24 hrs-a-day, 7 days-a-week, and 50 weeks-per-year. To operate the plant in such a manner, a constant supply of biomass is necessary. Switchgrass is harvested from June to February in the Southeastern US. So, sufficient material needs to be stored either at the processing plant or at on-farm storage locations known as Satellite Storage Locations (SSLs). To store a 3-month supply of material at the processing plant to supply during non-harvest period (March, April and May) requires the number of loads received at the processing plant during the harvest months (June to February) to be increased by 33% when compared to a 12 month delivery schedule. Such an increase cannot be handled by a receiving system designed to operate at or near optimal capacity all year around without a significant performance penalty. It is more cost effective for the processing plant to receive a steady stream of raw material year around. It is also impractical for the receiving system to remain idle during the three months when harvest does not occur. To avoid the resulting cost penalty, SSLs are used, so that equal deliveries can be scheduled every month.

Cundiff et al.,(2004) proposed using SSLs with crushed rock (gravel) surfaces as storage/collection points for bales. Multiple fields will share a single SSL, thereby centralizing storage/collection/loading operations in a given SSL's service area. This allows the use of specialized machines to load trucks faster and thus service the plant with fewer trucks. Cundiff (2004) estimated that such a storage location will cost $2.70/m$^2$. With 8% compound interest (CI), 7 years return on investment (ROI), and SSL emptied once every year, the cost of storage was estimated at $1.55/bale ($3.44/Mg).

### *3.4 Analysis of Biomass Potential Using GIS*

Downing and Graham (1993) simulated/analyzed cost and supply potential of short rotation woody crops (SRWC) for the Tennessee Valley Authority (TVA) as an alternate fuel for coal-fired power plants. The study considered: a) amount of crop and pasture land in a county, b) quality or soil types, c) expected output from a given county based on properties a and b, and, d) profits from current conventional crops in a county that will be replaced by SRWC. As the demand for SRWC went up, the cost (per dry Mg) that the plant required to pay for its supply went up from $28 per dry Mg (initially) to $93 per dry Mg for a supply of 74 million dry Mg.

Noon (1993) extended this study by using a GIS-based decision support system called "Biomass Resource Assessment Version One" or BRAVO to estimate the cost per dry Mg of SRWC (delivered) to any one of twelve coal-fired plants in the TVA region. BRAVO (Noon and Daly, 1996) used: a) current mill residue quantity and location, b) logging residue quantity and location, along with c) county level data on SRWC potential to compile a biomass resource base. This data was then used to compile potential biomass resource quantity and locations in the TVA region. SRWC's entire potential was assumed to be located at the center of a county to simplify calculations. Travel distances from these biomass demand points were calculated by "shortest distance algorithm" over the road network as determined by GIS. This distance was then used to calculate transport cost from a biomass source. An expected moisture content ratio was used to calculate SRWC's true cost-per-dry Mg (delivered) to its demand point.

It is important to recognize that the shortest path between two points in a road network may not always be the most economical/practical due to speed limitations on secondary and tertiary roads (Class II and III) that a shortest path algorithm may select. That is, truckers prefer traveling on highways, even if there was a distance penalty, as long as they save on travel time and fuel. These savings are mainly due to relatively constant and higher speeds (80 km/h) on primary roads (Class I), due to their reduced stop-go conditions. Shortest path algorithm, when used without factoring in this savings, will penalize biomass locations that are at a greater distance (geographically) with a lower travel time and give undue benefits to locations that are geographically closer, but with greater travel times.

Graham et al. (1997) used BRAVO model to calculate expected cost to deliver biomass (SRWC) to 21 regularly spaced locations in the state of Tennessee, to characterize geographical variation in biomass prices in that state. The demand for biomass and the percentage of potential biomass available (called farmer participation rate) were varied to observe the effects of such changes on price of delivered biomass. A circle of radius 120 km (75 miles) was defined as the procurement area for the study. As expected, increasing plant demand (with constant farmer participation rate) or decreasing farmer participation rate (keeping demand constant) increased biomass prices (delivered) due to increases in travel distance needed to procure required amount of feedstock.

In fact, Graham claims, "Halving participation or doubling demand will have the same effect on marginal cost of supply." It is important to note that Graham's 1997 study did not include any cost for loading or unloading biomass. If such a cost were included in that model, Graham's statement may not hold. That is because, doubling demand will double the number of loads needed to satisfy plant demand. That means, load/unload operations will be doubled and there will be an increase travel distance, as biomass sources located further away from the plant will be tapped. On the other hand, halving farmer participation will force the plant to tap locations that are further away, but there will be no doubling of load/unload operations. That is, the only effect will be an increase in transportation cost.

Graham et al. (1996) used GIS-based modeling to analyze geographic variations in potential biomass supplies and to determine optimal locations to place a biofacility (processing plant in this dissertation) of known demand. Graham used: a) county boundaries b) soil type map, c) land use map to construct a 1 km x 1 km grid dataset (or raster dataset) of cropland availability for the region under study. This grid, along with the proportion of cropland in the county currently planted to the dominant and minor crops was used to determine potential supply of biomass from a respective cell. Farm gate price for this biomass was determined, as a function of a) returns to land management from the current mix of conventional crops, b) fraction of harvested crop that reaches the conversion facility, with farmer assuming all losses, c) annualized energy crop production cost and d) average annual energy crop yield over the lifetime of the crop.

Graham's model calculated expected returns to land and management from the current mix of conventional crop as a function of: a) conventional crop yield, b) corresponding market price, c) production cost, and d) relative weight to crop type I, (i.e. dominant crop vs. others). The potential supply at any cell was then calculated as a function of a) proportion of crop land available for biomass production, b) average annual yield of energy crop over its lifetime, c) fraction of harvested crop which arrives at the conversion plant, and, d) percentage of cropland in a 1 km x 1 km cell.

Roads were assigned speeds based on their categories. Class I or primary roads, usually divided four lanes, were assigned 80 km/h (50 mph). Class II or Secondary roads and Class III or tertiary roads were assigned 48 km/h (30 mph). Travel time on the road network was calculated by dividing a road segment's length by its speed parameter. This travel time "cost" was used to compute shortest travel time path from every node to every other node in the road network (Noon et al., 1996b). Cost per Mg to transport biomass was then calculated based on: a) calculated travel time, b) a cost factor associated with travel time, c) travel distance along the shortest travel time route, d) a cost factor associated with travel distance, and, e) cost to load/unload these trucks.

The marginal cost to supply a given amount of biomass to a specific location was then calculated based on farm gate price and transport cost. This cost was then used to create a surface map of delivered biomass cost surface for the study region. The cell with the lowest total biomass cost was then deemed an optimal location to place a biomass conversion facility for a specific capacity.

Graham extended the model to look for alternate/multiple locations for biomass conversion facilities by eliminating the cell containing the optimal value in the previous step and its corresponding biomass sources. All steps for calculating transportation cost were then recomputed. The cell with least marginal cost from this run was deemed the next optimal location. Graham argues that such a scenario is more likely to occur, as conversion facility will enter into long-term contacts with farmers. But such a system of placing optimal locations will result in the second plant paying more per Mg of biomass (delivered) than the first plant.

Zhan et al. (2005) analyzed cost to supply required feedstock for a switchgrass-to-ethanol conversion plant in Alabama under fixed and discriminatory pricing policies. Farm gate prices and transport calculations were computed as by Graham (1996). Fixed cost pricing added farm gate and transport cost to determine the minimum price that a conversion plant needs to pay farmers to satisfy its demand. Transport cost and farm gate prices were separate variables for discriminatory price calculation. That is, farmer got paid for biomass, and the plant was responsible for transport. They conclude that discriminatory pricing is always cheaper than fixed pricing policy and optimal location of a plant depends on plant size.

It is important to note that this study penalized locations closer to Alabama’s borders, as production areas from surrounding states were not considered. More over, calculations for on-road travel were computed from node to node and then estimated as a straight-line distance from that node to any cell. Given that there were only 884 nodes for over 139,000 cells, this calculation could significantly impact travel time, distance, and cost calculations. This model failed to account for higher farmer participation rates in areas closer to a conversion plant under fixed pricing policy as they will make a higher profit than others due to their low transport cost to the facility.

The key issue was where the biomass changed hands from the farmer to the plant. A business model where every farmer is given the same opportunity to participate and make profit is the fairest model. To provide this opportunity, the conversion plant must buy the biomass in the SSL and then be responsible for the transportation cost. The conversion plant would have control of the delivery schedule and would be an essential management option required to optimize the whole logistics system.

## *3.5 Optimal route generation using rasters*

Husdal (2000) showed a simple method for calculating the shortest path using rasters from point 1 to point 2 when the distance to get to any cell in the raster from the point is known. For example, let us assume that point1, located in a 4x4 1m raster. The numbers in each cell represents the distance to the mid point of the raster from the midpoint of point1.

Point 1:

| | | | |
|---|---|---|---|
| 0 | 1 | 2 | 3 |
| 1 | 1.4 | 2.4 | 3.4 |
| 2 | 2.4 | 2.8 | 3.8 |
| 3 | 3.4 | 3.8 | 4.2 |

Point 2 is also located in the same raster and the following grid represent the distance to the mid point of the raster from point2.

Point 2:

| | | | |
|---|---|---|---|
| 4.2 | 3.8 | 3.4 | 3 |
| 3.8 | 2.8 | 2.4 | 2 |
| 3.4 | 2.4 | 1.4 | 1 |
| 3 | 2 | 1 | 0 |

To calculate the shortest path from point 1 to point 2 on this raster, we simply add these two rasters. The cells with the minimum value will represent the shortest path from point 1 to point 2.

Adding point 1 and 2:

| | | | |
|---|---|---|---|
| 4.2 | 4.8 | 5.4 | 6 |
| 4.8 | 4.2 | 4.8 | 5.4 |
| 5.4 | 4.8 | 4.2 | 4.8 |
| 6 | 5.4 | 4.8 | 4.2 |

To determine the optimal location with more than two points, the additional point's distance raster is added. The cell with the minimal cost/value is the optimal location. Note that in the case of two points, optimal path is a series of optimal points (multiple optimal solutions)

Point 3.

| | | | |
|---|---|---|---|
| 2 | 2.4 | 2.8 | 3.8 |
| 1 | 1.4 | 2.4 | 3.4 |
| 0 | 1 | 2 | 3 |
| 1 | 1.4 | 2.4 | 3.4 |

Adding points 1,2 and 3

| | | | |
|---|---|---|---|
| 6.2 | 7.2 | 8.2 | 9.8 |
| 5.8 | 5.6 | 7.2 | 9.2 |
| 5.4 | 5.8 | 6.2 | 7.8 |
| 7 | 6.8 | 7.2 | 7.6 |

Optimal

The above steps can be explained by a Mathematical equation as follows:

Let Xij denote cost to reach point j from cell i,

where,

i = cell number, 1 to m

j = total number of points under consideration, 1 to n

Then the above steps can be represented as:

Select min $\left\{ \sum_{j=1}^{n} X_{ij}, i = 1 \text{ to m} \right\}$

This method is used in calculating the optimal location for NPV and SPV using rasters.

## 3.6 Facility Location

Facility location problems are a special class of optimization problems where the objective is to locate a facility with minimal "cost", while satisfying all specified constraints. Facility location problems can be broadly classifies as discrete or continuous location problems, based on the way the problem's surface is defined. In our analysis, rasters are used as a starting point for production area availability. Since rasters are grids, only discrete location type of facility location problem is used in this analysis.

Discrete location problems usually consists of discrete sets of points (as in rasters) and are further classified into set covering, maximal covering, p-center, p-dispersion, p-median, fixed charge, hub and maxisum problems (Drezner and Hamacher, 2002). Each subtype mentioned above differs from others by the objective function being optimized.

In a set covering problem, the objective is to minimize the total number of facilities needed to cover all the demand points. In a maximal covering problem, the objective is to arrange a fixed number of facilities so that the maximum demand is covered. A p-center problem minimizes the maximum distance any demand point is from its facility. A p-dispersion problem maximizes the distance between any two facilities. A p-median problem minimizes the demand weighted total distance between demand nodes and the facility. A fixed charge problem is an extension of p-median problem, with capacities on facilities introduced. Hub location problems deal with multiple carrier modes and minimize average per km transport cost or total delivery time. A maxisum problem maximizes the weighted distance between facilities.

In this analysis, a proposed facility will be located in each production region, so that the total travel time to all SSLs is minimized. This representation of the problem follows a p-median representation of facility location problem.

## *3.7 Simulation and Biomass*

The best way to study a system is to experiment with the actual system. When this is done, there will be no question of the validity of the results obtained. As there are no fiber-to-ethanol conversion plants in operation at present for us to study, we are forced to look for alternate systems that could be used as models for our hypothetical system.

Modeling can be done with physical or mathematical models. A physical model is an iconic model. Examples of iconic models are miniature physical models used in air tunnel tests in the aviation and automobile industries. Mathematical modeling can be further divided into simulation modeling and analytical modeling. If the system under consideration has simple relationships that can be expressed as mathematical equations, analytical methods can be used to solve for the solution (Law and Kelton, 2000). In our case, since we cannot form these exact mathematical equations due to the stochastic nature of the system, we will use simulation-modeling techniques to model the system.

Simulation modeling can be divided into continuous simulation and discrete-event simulation. Systems where the state variables vary continuously with time are modeled with a continuous simulation. Examples of such systems are heat transfer in a metal bar. Discrete-event systems are those in which the state variable changes at a particular (discrete) point in time. An example of such a system will be “number of chairs in inventory at a retail store xyz.” The number of chairs can only decrease by integers and only when the sale takes place (at a discrete point in time).

In this study, our physical model is the cotton gin (Note: This physical model is different from the iconic model described in the above paragraph). What is learned from this model will be applied for the development of a discrete-event mathematical model of the biomass logistics system.

### *3.7.1 Steps in a simulation study:*

Banks and Carson (2001) describe the steps followed by a simulation analyst to obtain a good model and simulation study. These steps are discussed below.

**Step 1. Problem formulation:**

The first step in a simulation study is to define the problem (Note: This problem statement is not the same as the one used in systems engineering process). The problem can be worded either by the client or by the analyst. When the analyst words the problem statement, the client should understand and agree with the assumptions and simplifications made by the analyst.

**Step 2. Setting of objectives:**

In this step, the expected results or the questions that will be answered by the simulation study are recorded. It will also include a statement on the various scenarios that are to be examined. It will also include project start date, end date, personnel required, hardware and software requirements, and other relevant information.

**Step 3. Model conceptualization:**

A conceptual model abstracts the real world system under analysis, by a series of mathematical and logical relationships concerning the components and structure of the system. Usually a simple model is built and the model is allowed to grow in complexity, until the desired fidelity is achieved. This is done to avoid building a more complex system than required to achieve the same level of confidence in the results produced by the model.

**Step 4. Data collection:**

The most difficult aspect of simulation input modeling is data collection. In some cases, it is impossible to collect data, especially when trying to model a proposed system (as in our study). However data from similar systems can be used to approximate the input data.

**Step 5. Model translation:**

The conceptual model constructed in step 3 (Section 2.3.3) is coded into a computer-recognizable form. This is the operational model that will provide us with the answers to questions set initially.

**Step 6. Verification:**

Verification is concerned with the operational model. This step is required to check if the model that was coded is working properly. This step is performed using debuggers and or an interactive run controller.

**Step 7. Validation:**

Validation is the determination that the conceptual model is an accurate representation of the real system. If there is an existing system, comparison of the output of the simulation program with the output of the existing system can validate the model.

**Step 8. Experimental design:**

For each scenario that has to be run, we will have to determine the length of the run, the number of the runs, and the manner of initialization, as required.

**Step 9. Production run and analysis:**

Production runs, and their subsequent analysis, are used to estimate measures of performance for the scenarios that are being simulated.

**Step 10. Number of runs:**

Based on the analysis of the runs that have been completed, the simulation analyst determines if additional runs are needed and if any additional runs need to be simulated.

**Step 11. Documentation and reporting:**

If the simulation model is going to be used again by the same or different analysts, it may be necessary to understand how the simulation model works. This will also simulate confidence in the model, as the stakeholders can easily duplicate the model. When the simulation model is modified at a later date, the documentation facilitates this process by helping to understand the original model.

**Step 12. Implementation:**

The simulation analyst should act more like a (unbiased) reporter than an advocate. The report produced in the previous step should clearly outline the advantages and disadvantages with this particular system. It is up to the client to decide if he/she wants to use the results of the simulation study. Usually, if the client was actively involved during the previous steps, the likelihood of implementation is high.

## *3.8 Biomass Simulation:*

Nilsson (1999a; 1999b) developed a dynamic simulation model called "Straw Handling Model" or SHAM to analyze a hypothetical straw-to-energy system in Sweden. SHAM consisted of three Arena® modules, namely, a) location module, b) harvest & handling module, c) weather & field-dry module along with one Excel module to calculate system cost.

SHAM estimated a start date for harvesting operations based on region's established agricultural practices and assigned a hard stop date following 62 days of simulation run from the initial harvest. Location module then calculated procurement area for a given storage location based on expected yield and land use rate. Random coordinates were generated and used as field locations within that procurement region. Travel distance from storage location to any field was calculated as a function of Euclidian distance, multiplied by a constant called "winding factor" to address the fact that real roads between two points are not a straight line. A triangular distribution, based on expert opinion, was used to generate field sizes. Field sizes that had less than 5 ha were not harvested. Yield of straw per ha was computed as a function of grain yield, which was generated using a normal distribution with actual mean and standard deviation for the area under consideration.

Weather and field-drying module calculated internal moisture content of wheat straw by using a semi-empirical thin layer drying equation. Another semi-empirical formula was used to calculate equilibrium moisture content and to model drying/rewetting properties of straw. Accumulated precipitation was used to calculate external moisture content of straw.

Harvesting module determined when each field became available for harvest and was modeled using a Poisson process. The moisture content in the straw, along with precipitation was used to determine the time available for harvest. Front-end loaders were used to load one bale (1.2x1.3x2.5 $m^3$) at a time into transporters with 24 bales. Each load operation was assumed to take 30 minutes and each unload operation was also assumed to take the same amount of time. Harvesting equipment was typically assigned to one storage location’s procurement region until all fields were empty and then they were reassigned to the next storage location. First-In, First-Out (FIFO) method was used to select the first available field a harvester would service on any given day. The closest available field was serviced next and so on.

Field availability depended on soil moisture content, also modeled in this system. Setup times for harvest machines were assumed to be deterministic and exponential machine breakdown times were used to model delays due to breakdowns. Cost per Giga Joule (GJ) was calculated using: a) fixed cost to buy machines and buildings, b) variable cost of operating machinery, storage losses and materials, c) labor cost, d) losses due to inability to pick up material, and, e) raw material cost (in field).

Three different locations were modeled by SHAM in its initial run. With a hard stop on harvesting activities after 62 days, most replications had material left in the fields that could not be transported into storage. Average transporter utilization (% of time on road) of 30% was reported. Seventy percent of any transporter's time was spent on load-unload and waiting operations, with load-unload operations averaging around 27% of total duty time.

Nilsson also extended this model to use a) biomass from other sources with extended harvest times, b) increased acceptable moisture content, and c) increased number of storage locations from three to five. An increase in storage locations increased harvested straw as more number of storage locations translated to shorter travel times. Nilsson correctly noted that the loader was a bottleneck in this system and calculates projected savings with a load operation completing in 22.5 minutes rather than 30 minutes.

DeMol et al. (1997) used a simulation model called "Biomass Logistics Computer Simulation" or Biologics, to calculate energy consumption and cost to transport biomass from its source to its conversion plant. The cost included losses due to storage (dry matter and moisture) and it calculated transport cost. A pull type inventory model was used, enabling this system to "order" as needed from its previous nodes using a FIFO structure.

DeMol also used a mixed integer programming (MIP) formulation to calculate annual biomass flow with minimal cost. This procedure used the same parameters as the simulation study. Both models produced comparable results. DeMol noted that a simulation study only produced results for a given system, while an optimization model was needed to determine an optimal system.

Tembo et al. (2003) used a mixed integer-programming model (MIP) to determine biomass type, its harvest period, storage loss, inventory allocation, refinery size and its location to maximize net present worth of a biomass-to-ethanol system.  Tembo concludes that lignocellulosic biomass (LCB) gasification-fermentation method may produce ethanol that is \$0.12 per liter cheaper than current corn based ethanol production methods.

### *3.9 Traveling Salesman Problem*

The Traveling Salesman Problem (or TSP) is usually stated as, "Given n cities and the distance between any pair of cities, determine a tour that visits each city exactly once and returns to the initial city with minimum total travel distance." Although it is very simple to describe this problem, it is exceedingly difficult to solve for large values of n. There is no known polynomial time algorithm that can solve a TSP optimally. TSP assumes significance as several transportation routing problems and scheduling problems with job dependent setup times have similar structure (Burkard and Deineko, 1995).

In a TSP, a tour is defined as a sequence of n+1 integers taken from 1..n, with each integer representing a city and appearing at least once. The first and last integer in a tour is the same as the salesman always returns to his initial starting city. This city is referred to as a "Depot." Mathematically, a tour t is represented either as $t = \{i_1, i_2, i_3, \ldots, i_{n-1}, i_n, i_1\}$, where $i_1$ represents the first city visited, $i_2$ is the second city visited and so on till $i_n$ or as $t = \{(i_1, i_2), (i_2, i_3), \ldots, (i_{n-1}, i_n), (i_n, i_1)\}$, where each pair of cities is an ordered set. In either representation, the last leg of the tour where the salesman returns to his depot may be dropped as it is implicitly assumed (Bellmore and Nemhauser, 1968).

The distance between each pair of cities is given by a n x n matrix with non negative numbers. Each cell in this matrix is represented either by a distance (or cost) coefficient $d_{ij}$ or by an ordered pair, (i, j), where i and j vary from 1 to n. The total distance in any tour is the sum of all individual distances making up the tour and is usually represented as z(t).

There are several variations on the TSP in literature with each variation adding more complexity to the problem. Moscato (1998) lists some of the more common variations and a selection is presented here.

a. **Asymmetric TSP**: In this variation, the distance to travel from city i to city j is not the same as the distance between city j to city i. One way to solve this type of TSP is to add additional n cities. This doubles the number of cities in the problem but lets us create a symmetric TSP. These new cities act as ghost cities and are assigned a distance value of zero from the original cities. Table 3.1 and 3.2 present an example of a asymmetric distance matrices before and after ghost cities are introduced. The blank cells represent paths that are not feasible and can be populated with a very large value to prevent its use.

**Table 3.1 Distance matrix for an asymmetric TSP**

| | **A** | **B** | **C** |
|---|---|---|---|
| **A** | | 2 | 3 |
| **B** | 1 | | 5 |
| **C** | 6 | 4 | |

**Table 3.2 Distance matrix converted into a symmetric matrix**

| | **A** | **B** | **C** | **A1** | **B1** | **C1** |
|---|---|---|---|---|---|---|
| **A** | | | | 0 | 1 | 6 |
| **B** | | | | 2 | 0 | 4 |
| **C** | | | | 3 | 5 | 0 |
| **A1** | 0 | 2 | 3 | | | |
| **B1** | 1 | 0 | 5 | | | |
| **C1** | 6 | 4 | 0 | | | |

b. **TSP with distances 1 and 2**: In this variation, all edge weights (distances) have a value of 1 or 2. A performance ratio of 3/2 was obtained by Khanna *et al* (1998) using a non-oblivious local search.

c. **The Euclidean Traveling Salesman Problem**: A TSP in which inter city distances are the same as their Euclidian distances is referred to as Euclidean TSP

(Gutin and Punnen, 2002). In this form of TSP, the triangular inequality holds. That is, $d_{ik} > d_{ij} + d_{jk}$ for any i, j, k in {1, 2, .., n}.

The TSP in this research was modeled as an Euclidian TSP due to its simplicity. Section 3.9.1 looks at the solution techniques used by Concorde Ver 1.1 TSP solver, the program that was used in this research.

### 3.9.1 Concorde Solver, Version 1.1

Concorde follows the branch and cut method with iterative LP relaxation to solve TSP. The cut scheme was developed by Dantzig et al.(1954) in his paper "Solution of a Large-Scale Traveling-Salesman Problem" (Dantzig et al., 1954). Dantzig modeled the TSP as a linear programming problem and used the simplex method that was designed in 1947 (Applegate, 1998). The initial solution was a relaxed version of the TSP and provides a lower bound for optimal value of the TSP. If the optimal point of this relaxed version of TSP was not a member of the set of incidence vectors, a new inequality is added that "cuts" this optimal point. As the iteration progressed, the problem became tighter and tighter with each new iteration and finally a solution was obtained that it is a member of the set of incidence vectors.

Concorde projected the set of incidence vectors and the optimal solution from the LP relaxation into lower dimensional space before using a combination of template paradigm and TSP cuts (Applegate et al., 2001). Concorde used Clochard and Naddef's (1993) recommended criteria to branch as it reduced the size of the tree of subproblems (Applegate, 1998).

## 3.10 Vehicle Routing Problem

### 3.10.1 Introduction

Gendreau et al. (1994) states "The Vehicle Routing Problem (VRP) lies at the heart of distribution management." A basic version of this problem is generally referred to as single depot capacitated Vehicle Routing Problem with load splits. This version of VRP is setup to satisfy the demand at every node in a connected graph with a set of trucks, each with a capacity (C) and the ability to satisfy demand at one or more nodes.

In this dissertation, the demand point is the preprocessing plant and supply points are SSLs. The trucks in our model can pick up loads from more than one SSL till it is fully loaded, but have been restricted to a single SSL, as such a option is not practical.

Vehicle Routing Problems (VRP) are hard combinatorial problems (a typical VRP can generally be reduced to several Traveling Salesman problems) and relatively few VRP problems have been solved to optimality. Most of current research in this area focuses on developing heuristic algorithms that can provide “good” solutions. Generally, heuristic algorithms to solve VRP can be classified into four types (Christofides, 1985):

1. *Construction Algorithms:* These types of algorithms build routes by successively adding an unrouted city at each step according to any saving criterion until all the cities have been routed. These do not guarantee optimal solution. In fact, they hardly come close to optimal solution. They are used as a starting point for other, more efficient algorithms.

2. *Two-Phase Algorithms:* In two-phase algorithms, a feasible solution is obtained in first phase, which is then reoptimized by modifying the route scheduling or changing cities into alternate routes.

3. *Incomplete optimization Algorithms:* In these types of algorithms, decision rules in exact methods are replaced by heuristic procedures, in order to reduce the solution space necessary to be evaluated when an optimal solution has to be found. That is, some optimization steps are bypassed to decrease computational effort. Doing so destroys any guarantee of optimality, but gives us “good enough” results.

4. *Improvement Methods:* In these algorithms, starting from an initial solution, we attempt to find a better one by performing iteratively local perturbations on a current solution. Examples of such methods are Simulated Annealing, Tabu Search, Genetic Algorithms and Neural Networks. Since these algorithms start from a feasible solution and search for local perturbations, the final solutions are highly dependent on initial feasible solution and the path towards optimality (local). The (trick or) area of intense research is to find a method by which we can avoid getting stuck in local optimal solutions without increasing computational effort by a lot.

Metaheuristics is a term used to refer to algorithms that are designed as universal global optimization methods operating on a high-level solution space in order to guide heuristically lower level local decision rules' performance to their best outcome. In metaheuristic algorithms such as simulated annealing and Tabu search, successive neighbors of solution are examined, and the objective is allowed to deteriorate to avoid local optimal solutions. The rules which allow this deterioration to be accepted differentiates these methods from one another.

Simulated annealing is based on an analogy in metal annealing, a technique in material science, where a hot metal is allowed to cool under controlled cooling curve to obtain higher strength than with normal cooling. In simulated annealing procedures, the sequence of solutions does not roll monotonically down towards local optimum (unlike local search or steepest decent). Rather, the solutions trace an up and down random walk through a feasible set S, and this walk is loosely guided in a favorable direction. If the cooling is too rapid, then simulated annealing tends to behave like local search and gets trapped in local optima. If the cooling is too rapid, then we increase our computational effort without any appreciable increase in quality of final outcome. This rate of cooling is a variable that is problem specific and should be computed (or determined) empirically.

In Tabu search method, the main objective is to guide our sequence of solutions deterministically, unlike simulated annealing (which uses stochastic equations). This can be done by using different criteria. This criteria ensures that the loss incurred in the value of the objective function is somehow compensated for or at least justified for. An example of such an objective is, this worsening may allow sequences that have not been considered yet, to be explored. That is, to move from one locality to next.

A simple example of such a guidance criteria would be "least deteriorating" step. One version of such implementation is called steepest-decent-mildest-accent algorithm. In this version, we select a solution such that it maximizes Δ = current solution (say x) – next solution (say y). A major drawback of such a simple rule is, in the next step (from y), moving in the direction of x may be feasible, as it will provide a decrease in objective value. This will cause cycling and to avoid this, a dynamic list is maintained, which prohibits such swaps. Hence the name Tabu (or Taboo) search method. In this section, two improvement methods (metaheuristics), Tabu search method, Ejection Method and one optimal algorithm, Branch and Cut Method as applied to vehicle routing problem are described.

### *3.10.2 Tabu Search Heuristic*

#### *3.10.2.1 Problem Definition:*

Gendreau et al. (1994) considered the vehicle routing problem (VRP) under capacity and route length restrictions. To summarize this problem, there are n nodes. One of them is a depot. The other n-1 nodes are cities. A is a set containing all arcs between cities and between cities and depot. There is no arc from a city to itself. There is a nonnegative cost associated with moving from city i to city j. There can be fixed number of trucks (m) or variable number with an upper bound (M). Every route should start and end in the depot node. Every city must be visited only once. Each city has a demand and that has to be met.  There should not be any overloaded trucks (load <= q). Each city has a different service time. Maximum travel and service times are set. There is no fixed cost for owning and operating these trucks. There is only an operating cost determined by Cij.

### *3.10.2.2 Algorithm:*

In this version of Tabu search, Gendreau (1994) stored two solutions, S*, Ŝ* and objective values. S is a solution set with m routes R1 , R2 , .. , Rm where $1 \leq m \leq M$. Rr = {v0, v1, …. , vn, v0} and each vertex belonged to only one route, other than v0. There were two objective functions associated with this set, F1(S) and F2(S) (Refer to (Gendreau et al., 1994) for objective expressions.). F1(S) == F2(S) if and only if S was a feasible solution. If S was not feasible, then F2(S) had penalty terms depending on excess capacity and excess route duration. F1* and F2* denoted, respectively, the lowest values of F1(S) and F2(S). S* was the best known feasible solution and Ŝ* was the best-known solution (may be infeasible). The algorithm was split into two sub-algorithms. One was called SEARCH(P), where P was a parameter passed to the algorithm.

### *3.10.2.3 Procedure SEARCH (P)*

W is a set of cities that are allowed to be moved from their current route. This was equal to all nodes, except in run 3. See parameters and Algorithmic aspects section for more details. q is a number of vertices of W that can be reinserted into another route.

The algorithm started by initializing Tabu to null, and index to 1. It then consider the set S and randomly selected q cities from W. This step was referred to as vertex selection. For all vertices, the next steps were computed.

Cost of inserting that vertex into another route Rr, using GENI[1] algorithm and corresponding schedule S'. If move was Tabu, then don't compute, unless it improves either F1* or F2*.
Otherwise calculate F(S').
F(S') = F2(S') if F2(S') < F2(S) or
F(S') = F2(S') + a factor delta Δ.

[1] GENI is an algorithm that the author developed as an insertion procedure for Traveling Salesman Problem (Gendreau et al, 1992)

The candidate move yielding the least value of F and Ś was identified. Then the initial set S was processed through a post-optimization procedure to improve it. S = Ś unless F2(Ś) > F2(S'), S was feasible and S was not run through US[2] procedure in t-1 step. If US was not used and vertex v moved from one route Rr to another route Rs (s≠r), then reinsertion of v into Rr was declared Tabu until θ iterations has elapsed. θ was arbitrarily selected from [θmin , θmax]. update t, F1* and F2*, S*, Ŝ*, m and delta. Double alpha and beta values if all previous h solutions were infeasible. If they were feasible, then halve them. If F1* and F2* have not improved in the last nmax steps, then terminate. This parameter h controls whether the algorithm performs a global or local search.

### *3.10.2.4 Main Algorithm:*

Several initial solutions were generated. That was because as any local search method, Tabu search procedure will heavily depend on initial starting solution. SEARCH procedure was used on these for a limited number of steps and some promising solutions were selected as a starting point for main algorithm.

Initialization: Set alpha = beta = 1 and F1* = ∞. Convert 2-D graph into 1-D with horizontal angle.

Run 1: Repeat this step λ (an input parameter) times. Randomly select a city i and use a vertex sequence {v0, vi, vi+1,…,vn, v1,…,vi-1}to construct a tour on all vertices using a heuristic for TSP. Starting from v0 , create at most M routes by following the tour. Assign cities to trucks up to but not including city j, where adding city j will exceed truck's capacity or length constraint. If cities could not be split to include all cities in m trucks, all remaining cities after adding loads to the last truck, were assigned to truck M, making that solution set S infeasible. Update F1* and F2*, S*, Ŝ*. Then call SEARCH (P1) algorithm. If F1* improves (<∞), then S = S* else S = Ŝ*.
Run 2: Call SEARCH (P2). If F1* improves (<∞), then S = S* else S = Ŝ*.

[2] US is an algorithm that the author developed as a post-optimization procedure for Traveling Salesman Problem (Gendreau et al, 1994)

Run 3: Call SEARCH (P3). If F1* improves (<∞), then S* was the best solution, else no feasible solution was found.

### *3.10.2.5 Parameters and Algorithm aspects:*

The term delta (Δ) was a factor used to implement a diversification strategy. That is, vertices that have been moved frequently were penalized by adding a term to its objective value proportional to its frequency of movement. This forced the procedure to look for other vertices, thus broadening the solution set. Care should be taken while selecting Δ, as too large a value will make good solutions hard to find. At the same time, a small Δ value will not produce the desired diversification effect.

A variable Tabu list length was adopted to increase the chance of global optimality. This was based on earlier work done in this field. Using these values for alpha and beta will force them to not have values with only feasible or infeasible solutions. That is, alpha and beta values will automatically arrive at values that will present a mix of feasible and infeasible solutions. Dividing initial tour into routes can be considered as a bin-packing (knapsack) problem. Therefore, If n = M, then optimality could be claimed. Otherwise, no such claim can be made. W was always equal to V\{v0} except in run 3, where vertices that have moved often were used and will more likely result in an improvement.

### *3.10.2.6 Results Obtained and Conclusion:*

Different problems were considered for analysis. Problems that had only capacity restrictions were considered initially, followed by problems with both capacity and route length restrictions. In some problems cities were randomly generated in a plane, while in some others, they were clustered. Gendreau claimed that this algorithm produced better results than all "classical" algorithms. It generally produced the best-known solutions, which was very good as VRP is NP-Hard. The authors felt that using GENI algorithm and allowing infeasible solutions with a penalty term helped this algorithm to give better results by avoiding local optimal solutions.

This algorithm was also very flexible, as there was no need for a feasible solution to start with. Even though problems with dissimilar vehicles were not considered, they can be easily incorporated in this algorithm. Assigning specific trucks to cities can also be handled. Since this was a metaheuristics method, the algorithm will have to be tailored to the shape of a particular problem. This involved selecting input parameters. The authors also observed that there was no relationship between problem size and computational time. The moment at which the best solution was obtained was very unpredictable. This can be attributed to the fact that solutions could be examined only after the algorithm terminated.  Overall, this algorithm provided very good results with a moderate increase in computational effort. This moderate increase was attributed to the two external procedural calls to GINI insertion and US post-optimization procedures.

### 3.10.3 Subpath Ejection Heuristic

#### 3.10.3.1 Introduction:

Ejection chain methods are a subclass of variable depth methods, popularized by Papadimitriou and Steiglitz (1998) in their book "Combinatorial Optimization: Algorithms and Complexity." Ejection chain methods extend ideas exemplified by certain types of shortest path and alternating path constructions. In this process, each transition from one solution to next comes as a pair of steps. The first component of such a pair creates a distortion and the second step creates a change designed to restore the system.

The ejection terminology comes from typical graph theory, where each of the paired steps begins by introducing an element (such as a node, edge or path) that disturbs the graph's preferred structure and is then followed by ejecting a corresponding element in a way that recovers the critical portion of the structure. Most of the time, the critical structure is not recovered in one single step. In such cases, a series of steps are performed till the structure is recovered.

An example of such a method is alternate path construction algorithm. Here, each node has a constraint on the number of edges that can enter it. To construct an alternate path, an edge is introduced that violates this constraint. So the next step is to eject one of the current edges to remain feasible. This means that another vertex will have lesser number of edges than required. This chain of steps continues till all vertices have feasibility. A reference structure is used to control these moves.

A reference structure is a special representation of feasible structures in which a very small number of constraints are violated. Finding a feasible solution from this reference structure will be trivial. The list of Tabu moves will be updated dynamically and will be reset at the beginning of next iteration. There are two types of Tabu lists in these algorithms, Tabu-to-Drop and Tabu-to-Add. The Tabu-to-Drop contains edges or vertices that were added in this construction and therefore should not be dropped. Tabu-to-Add contains list of edges or vertices that have been dropped by the current construction and therefore should not be added.

#### *3.10.3.2 Problem Definition:*

Rego (1998) considered the vehicle routing problem (VRP) under capacity and route length restrictions. The problem is summarizes as follows. There are n nodes. One of them is a depot. Other n-1 nodes are cities or customers. A is a set containing all arcs between cities. There is no arc from a city to itself. There is a nonnegative cost associated with moving from city i to city j. The maximum number of trucks are not fixed. The value of m (total number of trucks) is a parameter that has to be determined. The route should start and end in the depot node. Every city is visited only once. Each city has a demand and that has to be met. There should not be any overloaded trucks (load <= q). Each city has a different service time. Maximum travel and service times are set. There is no fixed cost for owning and operating these trucks. Only operating cost (Cij) is considered in this model.

This problem is very similar to the VRP problem considered by Tabu Heuristic procedure in pervious section (3.8.1) by Gendreau et al. (1994). The difference in this problem is that the number of trucks does not have an upper bound nor a fixed number of trucks. We also assume that all the trucks are identical, which eliminates any custom routing options.

#### *3.10.3.3 Flower Reference Structure Based Algorithm:*

Rego's (1998) algorithm was based on the Flower Reference Structure, which was defined as a spanning subgraph that consists of a path attached to multiple cycles representing routes. This is sometimes viewed as an extension of stem-and-cycle reference structure. There are five basic parts in this reference structure. They are stem, blossom, root, star and core. These terms are explained below.

*ROOT:* $v_r$ *is called the root of a flower. It usually lies in an extreme edge of a stem.*

*CORE:* $v_c$ *is called the core of a flower. It is the center of the flower and all cycles will start and end there. It is usually the depot.*

*STEM: A Subpath connecting* $v_r$ *and* $v_c$ *. That is,* $(v_r, \ldots, v_c)$

*BLOSSOM: Each cycle* $(v_c, \ldots, v_r, \ldots, v_c)$ *with* $v_i\ (i \geq 1)$ *belonging to exactly one rout is called a Blossom.*

*STAR: This describes the set of edges* $(v_c, v_s)$ *in a blossom.*

#### *3.10.3.4 Ejection Chain Process:*

In each step of Rego's (1998) algorithm, a Subpath of a route was ejected in the form of a stem. There are two separate class of rules, one for creation of initial flower structure and one for the transformation from one structure to another. At no point in time during this process does the core move. That is, the core vertex always remained the same. The chain started by creating a flower structure from the initial solution. There were two rules to do this.

Rule S1: delete an edge (vc , vj ) belonging to the star, thus transforming a blossom into a stem.

Rule S2: Insert an edge (vc , vi ), where vi is a vertex not adjacent to vc and deleting one of the edges (vi , vj ), thus dividing the cycle into one blossom and one stem.

For both these rules, vertex vj becomes the root vertex. For growing the chain, the two rules were used again.

Rule E1: Add an edge from a blossom to the root. Then select a route in the blossom to be deleted, such that it is either the successor or predecessor of the vertex in the blossom to which the root was added. The vertex then becomes the new root. If the new root was also the core of the graph, the structure was considered to be successfully reduced into a feasible solution with no stems and only blossoms.

Rule E2: connect the root to another vertex in the stem. Now identify another vertex that lies between root and selected vertex. Delete that edge that links selected vertex and the new vertex.

Trail Solutions: Trail solutions were obtained by linking root vertex to a vertex in the star and deleting the edge from selected vertex to core. This method removed one route. Another method was to link root and core vertexes. This method added an additional route.

#### *3.10.3.5 Main Algorithm:*

In the algorithm, there were two levels of Tabu search, a low level and a high level. The low level Tabu search was used to determine the edges that were added or deleted at each level of the chain. In order to prevent flower structures already considered, a condition that no deleted edge should be added at a subsequent steps was also incorporated. This created a Tabu list. The algorithm does allow the deletion of added edges unless that edge was added after deleting an added edge. This was required to assure that the solution can be transformed into other by ejection.

In Rego's algorithm, there was a chance that the solution will not converge due to rule S2 not used enough times to start. So a factor λ was used that penalizes rule S1. The high level Tabu search was a standard form of Tabu search and works by using different starting and search strategies. It used a diversification or an intensification strategy depending on the frequency of vertices' movement. Finally, an algorithm was used to reoptimize each route. This algorithm was based on post-optimization procedure of a Traveling Salesman Problem.

#### *3.10.3.6 Parameters and Algorithm aspects:*

In rule S1, since an edge was deleted, there will be a decrease in cost associated with such a move. This means that most of the time, rule S1 will be used and not S2. To prevent this, rule S1 was penalized by λ. The value for λ was subjected to a sensitivity analysis and no conclusions were found. But random variation in specified intervals were found to be advantageous and was used. If $\lambda < 0$, then S1 was heavily penalized. $0 < \lambda < 1$, then S1 was penalized with respect to S2. $\lambda > 1$, then S1 was favored to S2. The algorithm selected a value for θ randomly in a specified interval. User can control how this algorithm behaved (local or global searches) by varying this interval. Again, this random length of Tabu list was based on previous work, which claimed that random list length favors better solutions. Frequencies of deletion or addition of edges were also used to penalize or favor consideration of these edges. The multiplication of these frequencies by β, randomly generated between $[0.1\sqrt{n}, 0.5\sqrt{n}]$, will control intensification or diversification of the solution. The algorithmic complexity was found to be O(n3), even though the real complexity of one step of the algorithm was found to be O(n2).

#### *3.10.3.7 Results Obtained and Conclusion:*

Rego (1998) solved several problems from literature and compared solution value and computational effort. It was found that that this algorithm, in general, deviated about 2.5% from the best-known solution. Further improvements were obtained when specialized algorithmic parameters were used. Interestingly, this algorithm was compared with Gendreau's Tabu algorithm and found that this algorithm halved the processing time required to solve comparable problems. This procedure allowed the use of infeasible sets during search process, which aided in a more complete search method. The amount of "bookkeeping" for this method was very less when compare to other Tabu search algorithms. Moreover, the number of external procedural calls were also less than Tabu search method.

### *3.10.4 Branch and Cut Method*

#### *3.10.4.1 Introduction:*

In some implementations of an integer-programming solution procedure, the integer program (IP) problem is solved as a linear programming (LP) problem. If the resulting optimal solution is integer, the process is stopped. Else, we will have to "cut" this feasible solution from the solution set, so that the LP can be solved again to obtain a new solution. But care should be taken to not "cut" any feasible integer solution. Constructing a new set of constraint that cuts only fractional values and solving the resulting LP problem usually accomplishes this. This process is repeated until an optimal integer value is obtained.

In the procedure considered here, the authors (Bixby and Lee, 1998) make use of approximating knapsack equality polytopes associated with individual constraints of the TDS problem, and an approximating node packing polytope associated with a graph, called the conflict graph, obtained by considering all the constraints simultaneously to construct these new cutting constraints.

#### *3.10.4.2 Problem Definition:*

Bixby and Lee (1998) modeled a truck dispatching problem. There were p number of pickup points. Each pickup point had one or more loads (integer only). A truck was dispatched to a pickup location. One truck can pickup only one load. Multiple trucks are dispatched to a location in case of multiple loads at that location. Each driver was grouped according to his/her certification and location (Home Base). A program generated a lot of itineraries for each driver according to the driver parameter set and other regulations (example: DOT regulations, which set an upper bound on the number of hours a driver can be on the road, depending on the type of load carried). Incase of itineraries with same loads but with different order of pickup, preliminary elimination was done by selecting one with the lowest cost. The objectives of this problem can be defined as

*Minimize deadhead miles. That is, the number of miles a truck travels unloaded.*

*Minimize the time a driver is on-road.*

*Equalize loading of drivers*

*Standardize dispatching methods.*

### *3.10.4.3 Algorithm:*

The first step in Bixby and Lee's algorithm was preprocessing. In this step, duplicate, multiple and redundant constraints were removed from the problem to reduce problem size. This step was implemented by a Row Inclusion/Multiple Inclusion step. The procedure searched for rows that were effectively represented by other rows. That is, it found and eliminated redundant rows. A clique matrix was generated such that we select a node v which is part of complete subgraph containing Mi. If some variables were fixed to either 1 or 0, they were removed from the problem. A conflict fixing of variables also takes place, when one variable is fixed to 1.

A heuristic step was used to obtain feasible integer solutions for the problem. The heuristic considered here sequentially fixed variables and solved the corresponding LP. It also had conflict fixing and logical rules that were custom developed for the problem under consideration. This heuristic procedure terminated when an integer feasible solution was obtained or when the LP was infeasible. If the integer solution obtained was better than previous solution, upper bound (UB) was updated and reduced-cost routing was invoked. If not, then constraint generation was invoked.

In this algorithm, before a branching process was performed, global reduced cost fixing was performed at root node whenever an improved integral UB was obtained or whenever the objective value of relaxed LP improved. Local fixing was performed at nodes based on current UB and local LP values. Clique Matrix generation technique and chordless odd cycle technique was used to identify inequalities and to generate cuts. Constraints were also generated by identifying facets for individual knapsack polytopes, using the facet defining inequalities. Lifting procedure was used to tighten the generated inequalities.

#### *3.10.4.4 Parameters and Algorithm aspects:*

Fine-tuning and selection of various parameters were based on extensive numerical experiments on this particular problem. The frequency at which heuristic calls were made was also studied. It was found that calling the heuristic procedure at every node of search tree was not efficient. The final implementation called the heuristic every 8 nodes from the root.

#### *3.10.4.5 Results Obtained and Conclusion:*

The preprocessor, reduced-cost fixing algorithm, the heuristic and constraint generator was integrated into CPLEX solver, which performs as the LP solver. Fourteen instances of data were run and were compared with CPLEXMIP software and plain Branch and Bound methods. With smaller instances of less than 2000 variables, optimal solutions were already present. Branch and cut outperformed branch and bound in all but one problem on objective value. CPLEXMIP outperformed branch and cut in eight problems on objective values. The authors claim that this is because they did not modify the input parameters for their problem based on problem. With respect to computational time, branch and cut performed better than CPLEXMIP in all but one problem. On average this method reduced computational time by 74%. This was expected as branch and cut method “cuts” off solutions at the root node and also at the search node. Since using a cut-pool was determined to be ineffective, none was used in this implementation. Cuts were dropped when they were not used for more than four consecutive LP solves. Disabling knapsack cuts increased computation times by 17%. Disabling clique increased it by 54%, while disabling odd cycle increased it by 20%. This shows that clique graphs had the highest effect on computational time.

### *3.10.5 Comparison between solution procedures*

Even though similar problems were solved using different methods, no claims can be made that any one method is better than the other. In Tabu search process, we have to be careful about being stuck into locally optimal solutions. Even though the algorithm attempts to move forward even in an infeasible direction to increase its global optimal solution, it still is highly dependent on starting solution and multiple starting solutions have to be used. That problem was overcome by allowing even infeasible solutions, but with a penalty term.  It produced good solutions, but was the most computational intensive. It required a lot of time to solve, as it used two external procedures, one for insertion and one for post-optimality.

In ejection method, bookkeeping is reduced and Rego (1998) claimed that this increased their solution convergence speed. It also tries to avoid local optimal solution by moving in infeasible directions as Tabu method. It does that by using ejection methods. The main advantage of this method over Tabu method is that this method calls a post-optimization process only once. That happens only after we get a final route set. This means that the computational time is reduced with respect to Tabu search method.

Comparing this with the other two processes will be unfair as this is an method that produces optimal objective value. That is because in the branch and cut problem, the problem is simplified by the fact that each truck can service only one location. There were no routes to be generated. Even though this simplifies the problem, as we can see, even this simplified problem is NP-Hard. The authors used three different methods to generate cutting planes and this helps in reducing the computational time. Using flower reference structure to generate an initial solution for this problem will be trivial and that means we will be left only with optimizing routine.

### *3.10.6 Additional Case Studies on VRP:*

Barbarosoglu and Ozgur (1999) used a tabu search based heuristic algorithm to solve a VRP for an electronics manufacturing/Distribution company in Turkey. A multi depot, multi node problem was decomposed into several single depot problems and solved accordingly. Barbarosoglu and Ozgur was able to do so due to the special relationships in the problem which were used to decompose the VRP. The algorithm was tested on benchmark problems and was found to perform very close to Gendreau's Tabu search.

Baita et. al. (2000) solved a VRP for a bus service company with 2,500 trips, 80 locations, 40 lines, 200 buses. The requirements included minimizing the number of buses, minimizing number of line changes, minimizing number and length of deadheading trips and minimizing idle time of busses. The problem was solved by a classic assignment problem formulation of VRP, a heuristic based on logical programming and finally using an genetic algorithm. Baita noted that genetic algorithm had the worst performance and the assignment problem provided the best solution among the three methods.

## *3.11 Facility Location and Vehicle Routing Problem:*

Syam (2002) modeled a multi commodity, multi location problem, which consisted of a two level freight network with three facilities, three warehouses and two destinations. Syam attempted to simultaneously determine an optimal solution while considering a) locations of plant and warehouses, b) flow in network c) transport cost, and d) warehousing cost. Syam noted that due to nonlinearities and disconnects in a road network, analytical formula to solve a model have limited success.

The problem was formulated as an integer programming problem and two heuristic algorithms (Simulated Annealing and Lagrange formulation) were used to solve this model. Syam noted that while simulated annealing produced better results for small scale problems, there was a computational time penalty for this improved result. On larger problems, Lagrange method tended to produce better results faster than simulated annealing.

Wu et al. (2002) solved a multi depot location routing problem (MDLRP). Location routing problems are models in which both location (facility location) and routing (Vehicle Routing Problem) need to be solved. Wu's model extended traditional problems by considering multiple depots, multiple fleet types and limited number of vehicles per fleet type. Wu decomposed this MDLRP into a location allocation problem and a VRP. A simulated annealing heuristic algorithm was used to solve the problem.

### *3.12 Simulation of Paper Logistics:*

Lehtonen and Holmstrm (1998) noted that simulation software specific to paper industry's logistics are scarce in their research paper on Finnish fine paper industry. Lehtonen and Holmstrm note that the inventory levels of Finnish producers are higher than industry leaders. Four different paper mills were analyzed using just-in-time methodology. Simulation models were constructed to observe improvements. In three cases, the use of just-in-time methodology/techniques led to a decrease in inventory of 28% or more. These techniques also improved other characteristics such as delivery time, total number of products (SKUs) in stock, and reduced the lead time. The authors concluded that just-in-time methodology was applicable to paper logistics as long as these techniques were modified or tuned to specific production conditions.

Hameri and Lehtonen (2001) analyzed five paper mills in Nordic region and improved their performance by reducing paper machine cycle time, reducing product range (SKUs), supply chain integration and other measures. Hameri and Lehtonen estimated savings as large as $600 million per year or more can be achieved by dropping a high volume, low cost system in favor of a more flexible system.

Gallis (2002) used a network simulation language (SLAMSYSTEM) to develop a holistic model of logistics involved in a forest product industry geared primarily towards international export. The flow of forest products through different sub systems from production point to final foreign destination were modeled using with the help of nodes. Each entity had attributes that were tracked as a product flowed through the system. The system calculated inventory levels, cost associated with logistic movements. Six different scenarios were modeled and expected costs were calculated under different operating parameters. The study concluded that large savings could be achieved in this supply chain by reducing port operation times, there by reducing transit times and inventory levels.

Carino et al. (2001a; 2001b) developed a multi staged model of a vertically integrated wood product system. A multistage linear programming model with production and inventory decisions from procurement to marketing were modeled, along with their constraints. There were four stages of decision and three different inventory classes. The LP was then solved to optimality for a 12 month period and production-inventory decisions were determined. Sensitivity analyses were performed and the range in which the optimal solution holds were determined. Parameter analyses were performed and effects of various input parameters were determined. The new policy resulted in a 156% increase in profitability.

## *3.13 Knapsack Problem*

Knapsack problems belong to combinatorial optimization problems and are the simplest NP hard problems (Du Staff et al., 1998). Black (2005) defines NP hard as *"The* *complexity class of decision problems that are intrinsically harder than those that can be solved by a nondeterministic Turing machine in polynomial time. When a decision version of a combinatorial optimization problem is proved to belong to the class of NP-complete problems, then the optimization version is NP-hard."*

A special case of knapsack problems, where the objective is to minimize the total number of knapsacks used is referred to as a bin packing problem. A bin packing problem involves choosing items from a set, such that the total number of bins needed to store all elements from a set is minimized. More rigorously, a knapsack problem can be represented as:

Max $\sum_{i=1}^{n} X_i C_i$

subject to:

$$\sum_{i=1}^{n} X_i C_i \leq C$$

$$X_i \in \{0,1\} \forall i = 1..n$$

Here the objective is to maximize the total "value" of $C_i$ with a maximum constraint of C. There are several algorithms that have been developed, that can solve some cases of knapsack problems even with their NP hardness, by taking advantage of their special structures. Multiple knapsacks can also be modeled in a similar manner.

Max $\sum_{i=1}^{n} \sum_{j=1}^{m} C_j X_{ij}$

Subject to:

$$\sum_{j=1}^{m} C_j X_{ij} \leq C_i \forall i = 1..n$$

$$\sum_{i=1}^{n} X_{ij} \leq 1 \forall j = 1..m$$

$$X_{ij} \in \{0,1\} \forall i = 1..n, \forall j = 1..m$$

Both these models maximize the total value that is packed into the knapsacks, but it assumes that the total number of knapsacks is known apriori. When working on cotton module pickups, each truck's total available time per day can be considered as its total capacity (600 minutes = C). Each module has a cycle time associated with its pickup, which represents the "value" of each pickup. The goal then becomes "how do we pack these module pickup times into these 600 minute time slots, so that all the modules are transported in least amount of days?." As mentioned before, such an problem becomes a bin-packing problem, and is dealt in greater depth in section 4.6.

Scholl et al. (1997) developed an exact hybrid algorithm called BISON for solving one dimensional bin packing problems. The authors claim that the algorithm compares favorably with metaheuristic procedures like tabu search and also with branch and bound methods. Alvim et al. (2004) used the dual min-max problem to generate initial solutions and used a tabu search method to develop an hybrid algorithm for an one dimensional bin packing problem. Chan et al. (2005) used a genetic algorithm to solve a one dimensional bin packing problem in ion plating industry and show that significant performance improvements were possible with this algorithm. Coffman et al. (1996) provide an extensive survey of approximation algorithms for bin packing problems.

# Chapter 4 – Case Study of Cotton Logistics

## 4.1 Background

United States economic growth depends on continuous availability of low cost energy. This need for lower cost energy has assumed increased significance in the current economic and political scenario. More than 85% of energy consumed in year 2005 in the United States was from fossil fuels, namely coal, petroleum, and natural gas. Six percent of energy was produced from renewable resources, of which alcohol fuels was a mere 6% of the renewable energy total (Department of Energy, 2006).

This widespread use of fossil fuels and the resulting release of fossilized carbon dioxide and other green house gasses have been blamed for global warming, increasing sea levels and changing climatic patterns. This has led to a renewed global interest in fuels from biological sources; as they are usually zero contributors to greenhouse gasses.

The US Department of Energy's Biomass Research and Development Committee has set an ambitious goal of replacing 30% of current petroleum consumption by biomass and its products by the year 2030 (Department of Energy, 2003). To achieve this goal, various systems capable of harvesting, storing and transporting large quantities of biomass have to be designed and built.

There are no commercial fiber-to-ethanol conversion plants in operation today, on which a study can be based to model their transportation system. However, the transportation system of a cotton gin uses several components, or subsystems, that a fiber-to-ethanol system envisioned in this study will use. Most notably, both systems use trucks with modularized loads which are capable of road speeds. So a study was developed to review the current transportation system of a gin in southeastern Virginia, to gather operating parameters for a fiber-to-ethanol conversion system.

## 4.2 System Description:

### 4.2.1 Cotton Collection and Harvest

Cotton is usually harvested with a machine that pulls the fiber from the plant. Seeds, parts of the bole and pieces of stalk and leaves are also collected during harvest. This material is collected in a dump bin on the harvester and is dumped into a dump trailer as needed. The dump trailer transports this material to a module builder, usually located at the edge of a field. The module builder compresses this material into a 2.4 m wide x 2.4 m high x 6.1 m long (8ft wide x 8ft high x 20ft long) blocks known as cotton modules, with each module weighing anywhere from 4.5 to 8.2 Mg, depending on moisture content and other factors.

These modules rest on the ground and are covered with a fitted canvas or plastic cover as protection against rain. The modules remain on the farm until they are transported to the gin by module haulers.

### 4.2.2 Cotton Module Transport

Module haulers are "live-bottom" trucks designed to pull the truck beds back under the module, thus lifting it up onto the bed. The bed is then lowered to the horizontal position and the truck transports the module to the gin for processing.

With the current transportation system, the gin owns and operates these module haulers. Typically, when farmers have several modules built, they notify the gin and request pickup. The gin then schedules the module haulers to transport these new modules as soon as all previously scheduled modules are transported. That is, all modules are picked up on a First-In, First-Out (FIFO) basis.

An average ginning season in southeast Virginia ranges from 75 to 85 days, typically running from October 1 to December 15. This case study was conducted at Mid-Atlantic

Gin located in Emporia, VA. The gin gathered modules harvested from 5929 cotton fields in this surrounding region during 2001 ginning season. Figure 4.1 shows the location of the cotton fields as dots and the star represents the location of the cotton gin under investigation.

## *4.3 Simulation of Cotton Ginning Operations*

### ***4.3.1 Module Arrival Rate***

After the cotton modules were built, the farmer typically calls the gin during morning hours for a cotton module pick up, however, a small percentage of these calls occur during afternoon. The gin records the date, time and module numbers on a module call-in sheet. This information was used to compile a time series showing the number of modules that were called in during each day (Figure 4.2). For 2001, 2,141 modules were called-in to the gin and the simulation model was set to terminate when the total number of call-in's exceed 2,000.

In this simulation model, multiple module call-in's throughout the work day was replaced by a single module call-in at the beginning of a work day. This was done to simplify the simulation model without loss of information that the model can produce. These modules were assumed to be available for pickup at the beginning of each work day in which the call-in occurred. Figure 4.3 shows the frequency distribution of observed number of modules called-in and the beta distribution that was used to model that data.

The number shown beneath the bar on the horizontal scale is the value of the derived distribution at the midpoint of the bar. The mean for number of modules called-in (per day) was 27 and variance was 6.6. Kolmogorov-Smirnov test and chi-square goodness of fit tests were performed on this data and beta distribution and the differences were found to be statistically insignificant ($\alpha = 0.05$).

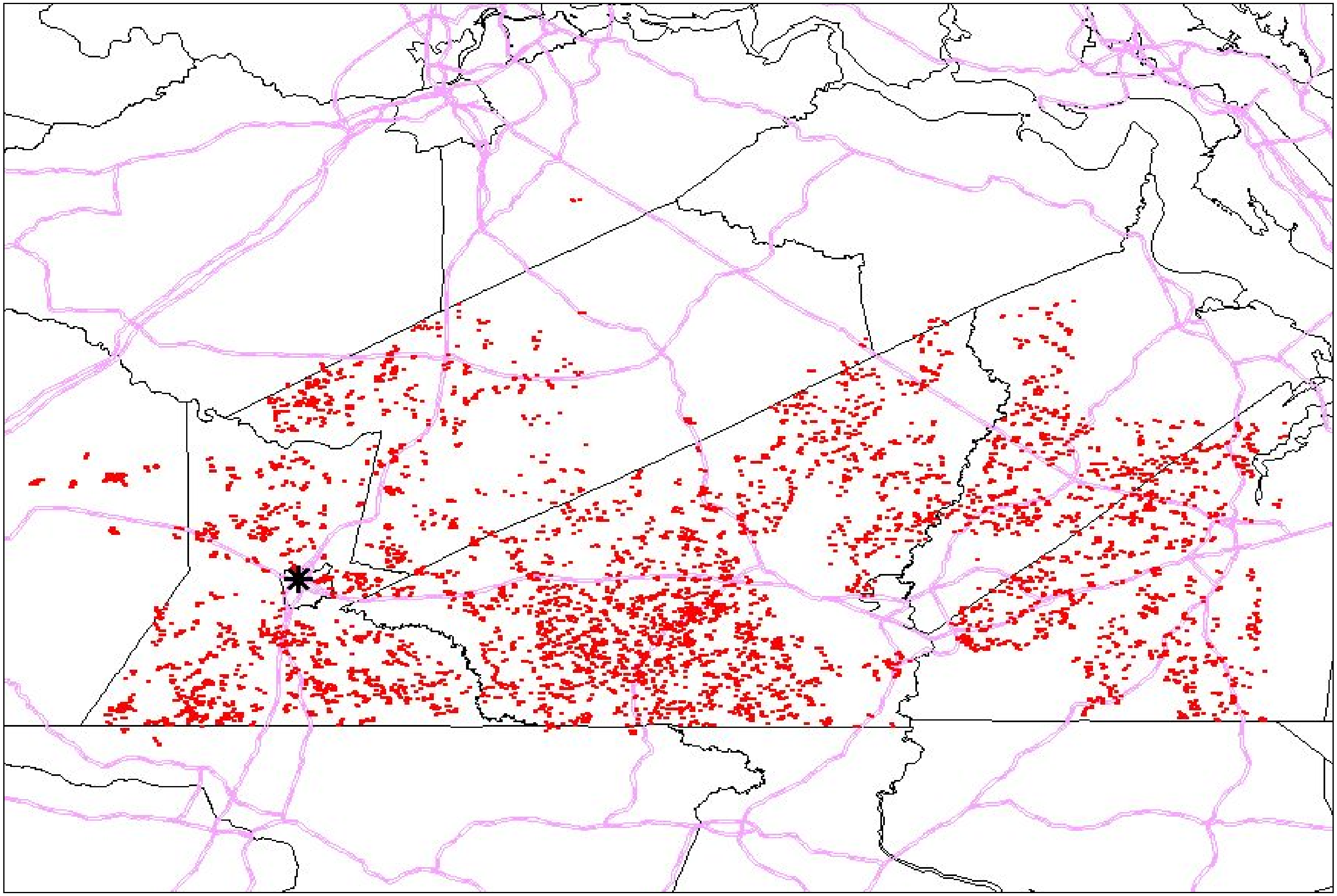

**Figure 4.1 Location of cotton fields shown as dots and cotton gin as a star located in Emporia, VA**

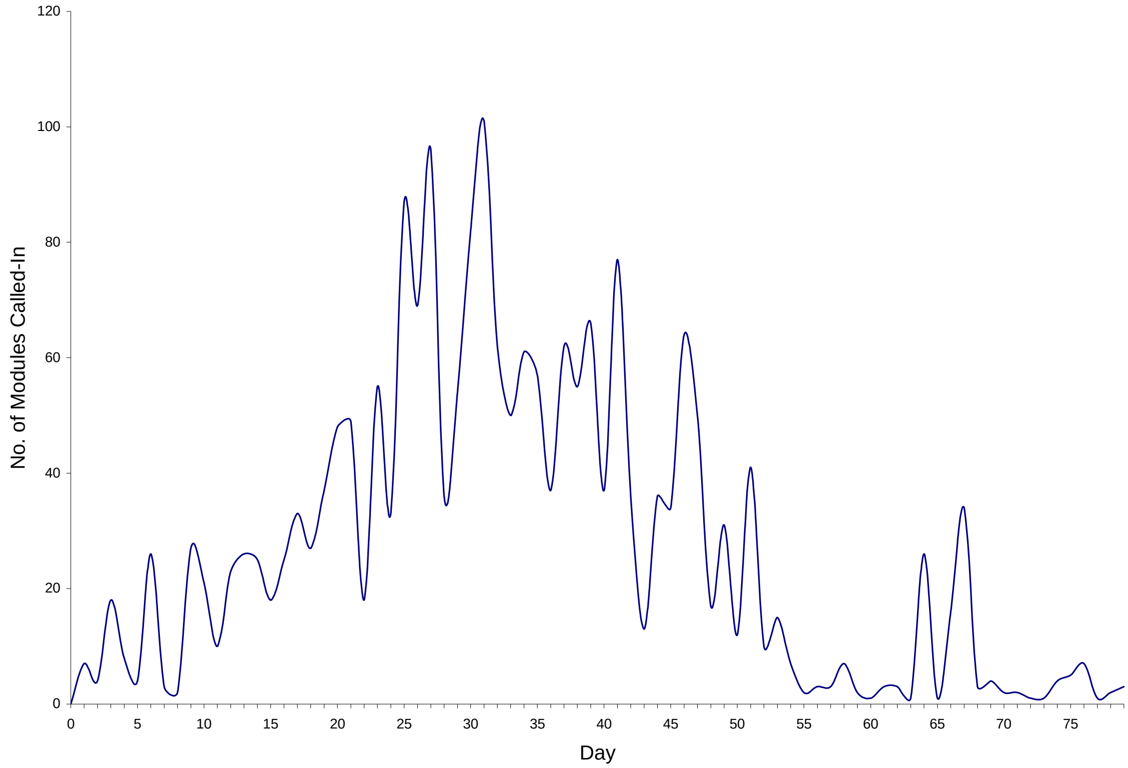


**Figure 4.2 Time series for module call-in rate at the gin for year 2001**

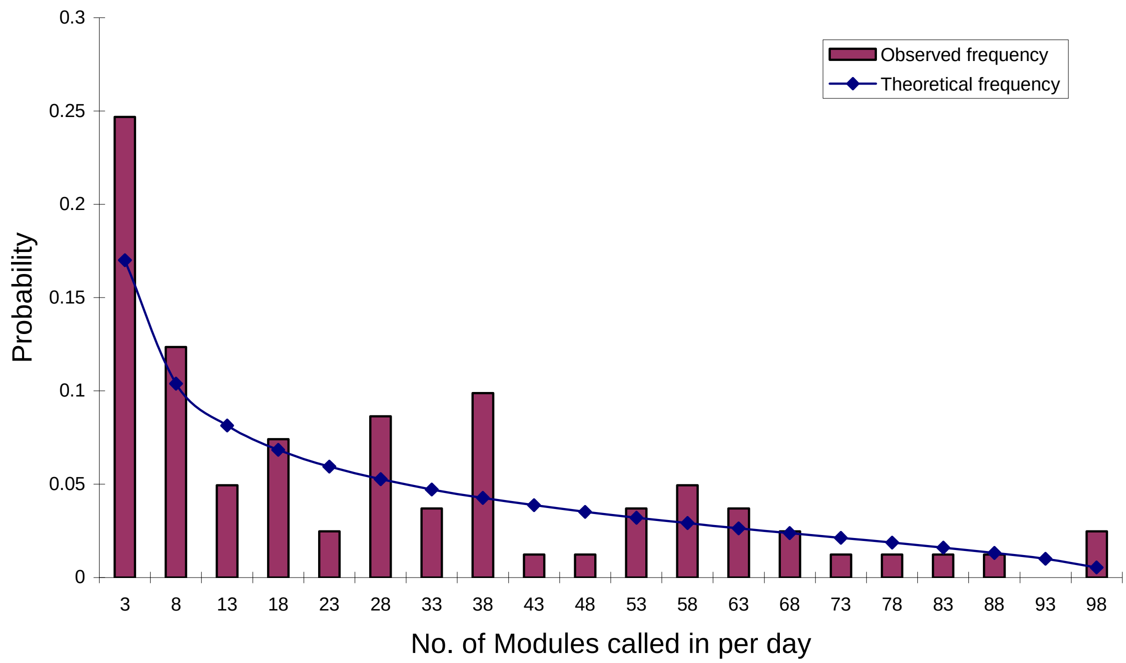


**Figure 4.3 Daily module call-in theoretical vs. actual frequency distribution**

### 4.3.2 Truck Cycle Time

After the gin is notified, module haulers are sent to pick up modules from the fields on a FIFO basis. That is, module trucks will transport all modules from a single farmer before they transport modules from the next farmer on the list. This policy is disregarded only when the gin is running short on inventory and there are modules available at shorter distances than the next location in the FIFO queue. Farmers do not like this practice, and the gin management avoids this strategy, if possible.

Truck cycle time consists of travel time from the gin to the field, module load time, travel time from the field to the gin, and module weigh in time. Time lost due to driver breaks and maintenance factors were not considered explicitly in this model, as they were factored into travel times of each truck. The gin maintains a record of module arrival times when the truck weighs in, but does not record its corresponding departure times. It was observed by the author during a field study that the module haulers continuously haul loads during the day. Therefore, the truck leave times was assumed to be same as the time records when the empty truck is weighed as it leaves the gin. This data was used to compile a frequency distribution of truck travel times, with loss of information on the first trip of any day (Figure 4.4). The number shown beneath the bar on the horizontal scale is the value of the derived distribution at the midpoint of the bin.

The gin owns and operates six trucks and all are assumed to be identical. Of these six trucks, one truck is exclusively used to load modules from the gin storage yard onto the conveyor that feeds modules into the gin for processing. The remaining five trucks are used to transport modules from the fields to the gin storage yard. Although the sixth truck is sometimes used to transport modules very close to the gin, such an event is rare and was not included in this simulation.

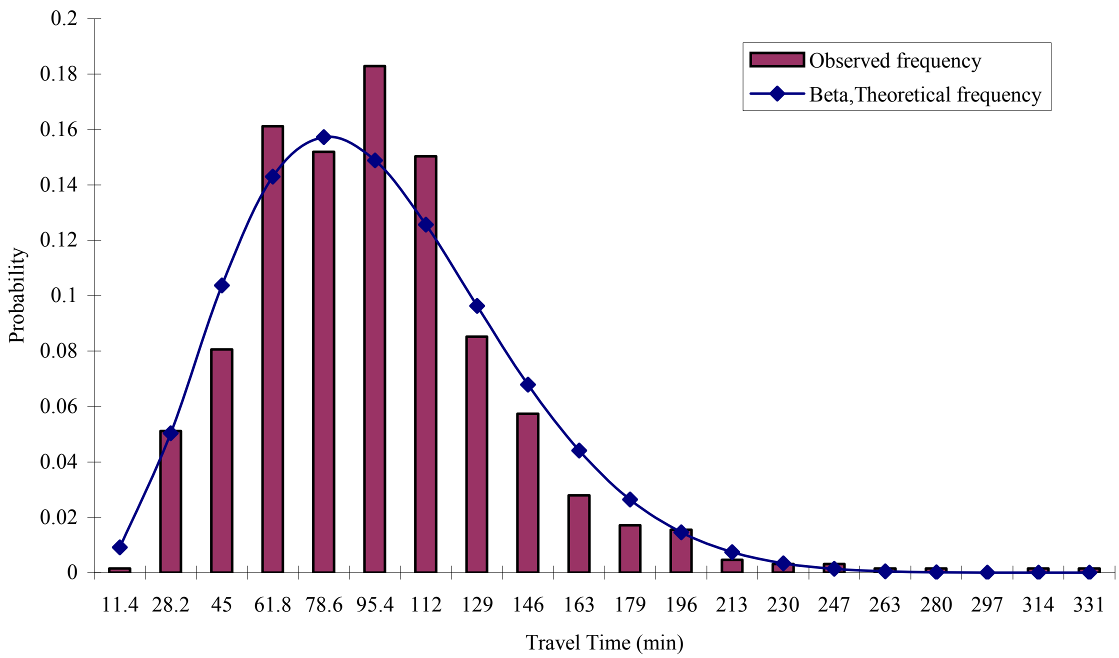


**Figure 4.4 Truck travel time histogram and beta distribution**

The trucks operate 10 hrs-per-day, 7 days-per-week during ginning season. The distribution of truck travel times has a long right tail with a mean of 95.6 min/trip and a standard deviation of 42.4 min. Due to the possibility of a truck breaking down or becoming inoperable for long periods of time, a beta distribution with a long but finite right tail, a1 = 3.6, a2 = 11.5, and, a scale factor of 400 was used. Truck breakdown and/or travel time 6 hours or more was very rare and those events were not considered in this simulation. Figure 4.4 shows this distribution superimposed over actual truck travel times. Kolmogorov-Smirnov test and chi-square goodness of fit tests were performed on this data and beta distribution and the differences were found to be statistically insignificant ($\alpha = 0.05$).

The shape of the beta distribution (for the truck travel time) is not expected to vary significantly from one season to the next, as the number of farmers who switch from one gin to another is small. On the other hand, weather or other annual road/field conditions may significantly impact travel times. Impact of such a change will be uniform, irrespective of travel times. To account for these seasonal differences, the mean travel time was increased by 10 and 20 minutes and decreased by 10 minutes to simulate its impact on the gin. Table 4.1 shows these distributions and corresponding means.

**Table 4.1 Probability models considered for truck travel times**

| Distribution | Mean (min) | Strategy |
|---|---|---|
| 400*Beta [3.6, 11.5] | 95.6 | Current truck travel times at the gin |
| 10 + 400*Beta [3.6, 11.5] | 105.6 | Increased mean truck travel time by 10 minutes |
| 20 + 400*Beta [3.6, 11.5] | 115.6 | Increased mean truck travel time by 20 minutes |
| -10 + 400*Beta [3.6, 11.5] | 85.6 | Decreased mean truck travel time by 10 minutes |

### *4.3.3 Cotton Gin*

Information on when the modules were processed by the gin was not available. A gamma distribution, based on expert advice of the gin manager, was used to model processing times for each module. In the worst-case scenario, the gin will process 20 modules-per-day. On a "good" day, the gin will process 50 modules-per-day. In a typical day, the gin will process 45 modules. The gin operates for two shifts per day, each shift operating for 12 hrs. Thus, the gin operates for 24 hrs-per-day during ginning season.

This data was used to calculate the distribution for processing time by the gin for each module. In the worst-case scenario, the gin processes one module every 24/20 hrs or 72 min. In the best-case scenario, the gin processes one module every 24/50 hrs or 28.8 min. In the typical day, the gin will process one module every 24/45 hrs or 32 min. A gamma distribution with $\lambda = 0.4$ hrs and a constant 0.2 was used to generate module processing times. An inventory of 100 or more modules was needed for the gin to start its initial processing.

## *4.4 Simulation*

Figure 4.5 shows the actual discrete event model used to simulate the cotton gin operations. Discrete event simulation software Sigma® (Custom Simulations, 2004) was used to run this model. The first event scheduled is “Start.” This event starts the simulation model and initializes the state variables. Next, an event “Day”, signifying the start of a workday, is scheduled. This event is set to repeat itself every 24 hours until the simulation is terminated. The event “Day” was set to activate events “MCall”, which schedules module call-in and event “Gin”, which starts the gin processing.

Module call-in event (MCall) is the first daily event and occurs once a day until 2,000 or more modules are called-in. Once the number of call-in’s exceeds 2,000, event “Day” will not activate event “MCall.” The module call-in distribution determined the number of modules that were called.

The event “Day” schedules the event “Gin” through event “P1.” Event “P1” prevents duplicate scheduling of event “Gin” and keeps track of gin operating status. Activating event “Gin” from event “Day” occurs only once if one of the two following conditions is satisfied.

1. The gin is currently not running and current inventory is more than 100 modules or,
2. The gin is currently not running and all modules expected for this ginning season were called in. That is, event “MCall” is no longer scheduled.

Event “MCall” activates “Truck1” to “Truck5,” where each event represents an individual truck in the logistic system, in that order. Each truck event was incrementally delayed by 1 min during this initial scheduling to prevent two or more trucks scheduled for the same module. These truck events were activated by event “Day” when event “MCall” is no longer scheduled. This was done to ensure that all modules are picked up. Depending on the number of modules waiting in the fields, trucks were assigned to modules and are transported to gin storage.

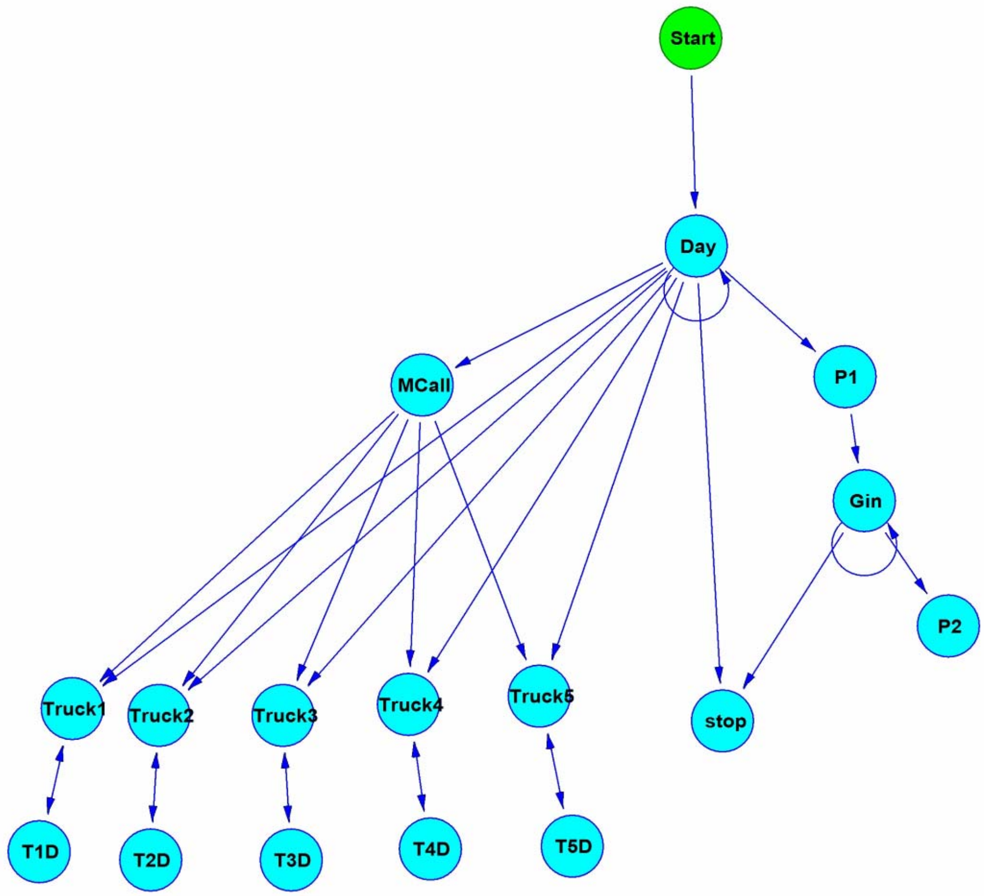


**Figure 4.5 Sigma® Discrete Event Model of Cotton Logistics, FIFO**

When a truck event was scheduled, the number of modules waiting for pickup was reduced by one to eliminate any chance of multiple trucks assigned to pickup the same module. The truck travel time distribution determined the time a truck takes to pickup a module and return to the gin. This travel time is coded into the time delay between "Truckx" and "T1x" events of each truck. At the end of this delay, the inventory at the gin went up by one. The trucks were scheduled to terminate their last trip after 10 hours of service every day and this was controlled by "T1x" events.

Ginning was the last operation to start and was not activated until inventory level at the gin reached 100 modules. Cotton ginning distribution was used to determine the time any one module spends in the gin for processing. Once the ginning process starts, it will not stop until all modules in the gin's inventory are used up. At this point, if there are more modules waiting to be transported, the gin shuts down until the inventory level is built past 100 modules. Event "P2" was used to record gin's operating status. If there are no more modules in the fields, the event "Gin" activates event "Stop" which terminates the simulation. A failsafe event "Stop" was coded from event "Day." This failsafe is activated if the gin has completed processing all modules but fails to activate event "Stop."

Five replications were run for each of the four travel time distributions. The data was averaged to compile the results. Gin utilization factor was defined as the ratio between sum of all module processing times to the time difference between processing the first module and the last module. Truck utilization factor for any truck was defined as the ratio between sum of all travel times by that total available truck time.  Where total available truck time was defined as 10 times the number of days available in the hauling season.

## *4.5 Results and Discussion*

Table 4.2 compares the truck utilization factors under different conditions. When the mean truck cycle time was increased from 95.6 to 105.6 min (an increase of 10 min/trip), the average truck utilization went up by 3.2% for the five trucks. This small change in utilization factor occurs because when all five trucks are operated under normal conditions, the maximum number of modules that can be hauled per day and truck utilization will be limited by availability of modules in the fields to be hauled and the restriction on truck operating time.

But when the truck travel times were increased, the number of modules hauled per day did decrease. Since there is no change in the number of operating hours or the number of modules called in, the trucks will have more modules waiting to be hauled and the truck can operate longer, causing an increase in truck utilization factor.

When the mean truck cycle time was increased by 20 min to 115.6 min, there was a corresponding increase in truck utilization factor to 89%, with no change in simulation length. This increase is due to increased module availability during the simulation run caused by larger truck cycle times.

As the truck cycle time was decreased by 10 min to 85.6 min, the number of modules available for pickup decreased and there was a drop in truck utilization factor from 77% to 73%. With decreased truck cycle times, the gin was able to build up its inventory faster and it was reflected in its increased utilization factor of 74% vs. 69% under normal truck cycle times.

**Table 4.2 Average truck and gin utilization rates and predicted processing season under different travel strategies.**

| Module Arrival Rates | Truck Travel Times (Min) | Number of Trucks Used | Avg. Truck Utilization Factor* | Avg. Gin Utilization Factor* | Avg. Simulation Length (Days)* |
|---|---|---|---|---|---|
| Beta [0.5,1.49]*101 | 400*Beta [3.6, 11.5] | 5 | 0.77* (0.63 - 0.85) | 0.69 | 80 (74 – 95) |
| Beta [0.5,1.49]*101 | 10 + 400*Beta [3.6, 11.5] | 5 | 0.80 (0.71-0.87) | 0.66 | 83 (77 – 93) |
| Beta [0.5,1.49]*101 | 20 + 400*Beta [3.6, 11.5] | 5 | 0.89 (0.81- 1.) | 0.67 | 83 (73 - 91) |
| Beta [0.5,1.49]*101 | -10 + 400*Beta [3.6, 11.5] | 5 | 0.73 (0.67-0.86) | 0.74 | 74 (64 - 79) |

*Average values of 5 replications and the range of simulated values are listed below the average.

Figure 4.6 shows the number of modules processed by the gin on any given day, as predicted by the simulation program. Once the inventory level reached zero, the gin stopped processing modules and the gin did not restart until inventory level was replenished to 100 modules. Days where both inventory and module call-in rates were low are represented by a long delay before ginning started (example days 41 to 46).

There were five days in which the gin did better than expected and processed in excess of 50 modules (Max = 55 modules). Although this is not a common occurrence, the gin had in the past processed at these high numbers, especially with low moisture content modules. The last day for this ginning season, as predicted by this simulation program was day 74 and 29 modules were ginned on this last day. The gin was operating from day 8 until day 74, for a total of 67 days, during which it was shut down three times, for a total of 14 days.

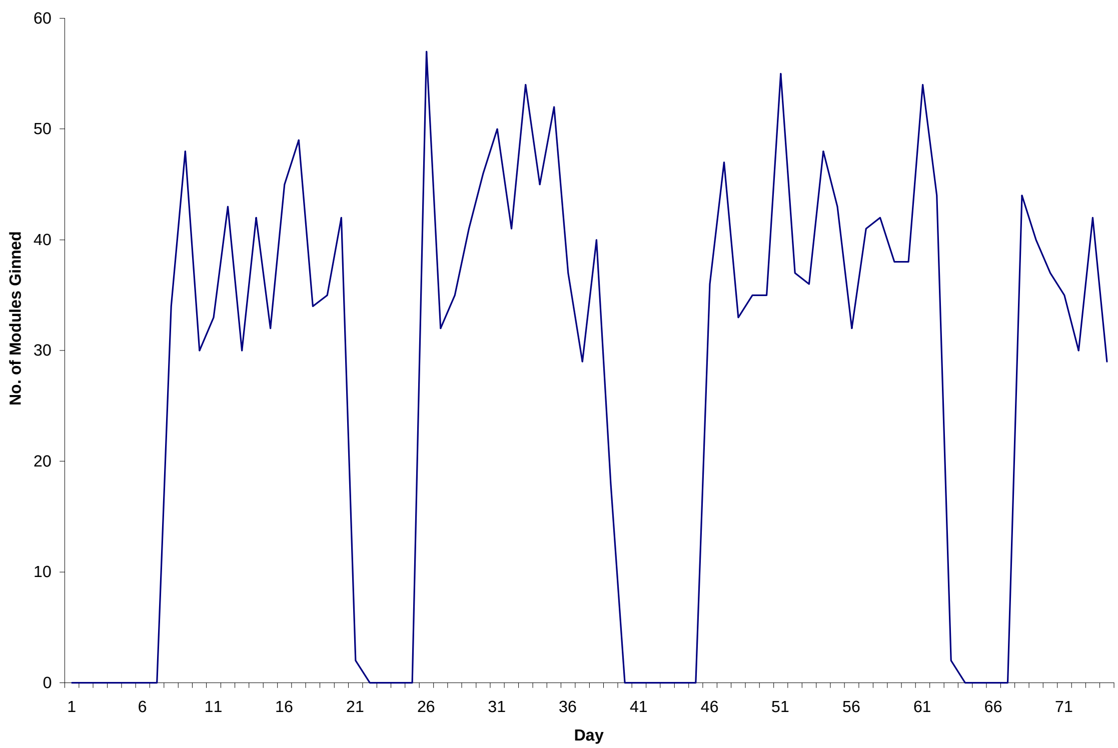


**Figure 4.6 An example output from a replication showing the number of modules processed by the gin on any given day under 400*Beta [3.6, 11.5] distribution (Day 0 = 10/1/2001).**

Figure 4.7 represents the number of modules waiting in the fields to be hauled under normal conditions while using five trucks. As the graph shows, there are numerous days when there were no more modules available after the initial trip to the field. An increase in the number of trucks will not have any effect on inventory level at the gin on these days. This lack of modules causes a corresponding drop in gin inventory level, causing delays in inventory replenishment. This bottleneck is beyond gin's control and cannot be overcome without sourcing from other farmers which could incure a cost penalty.

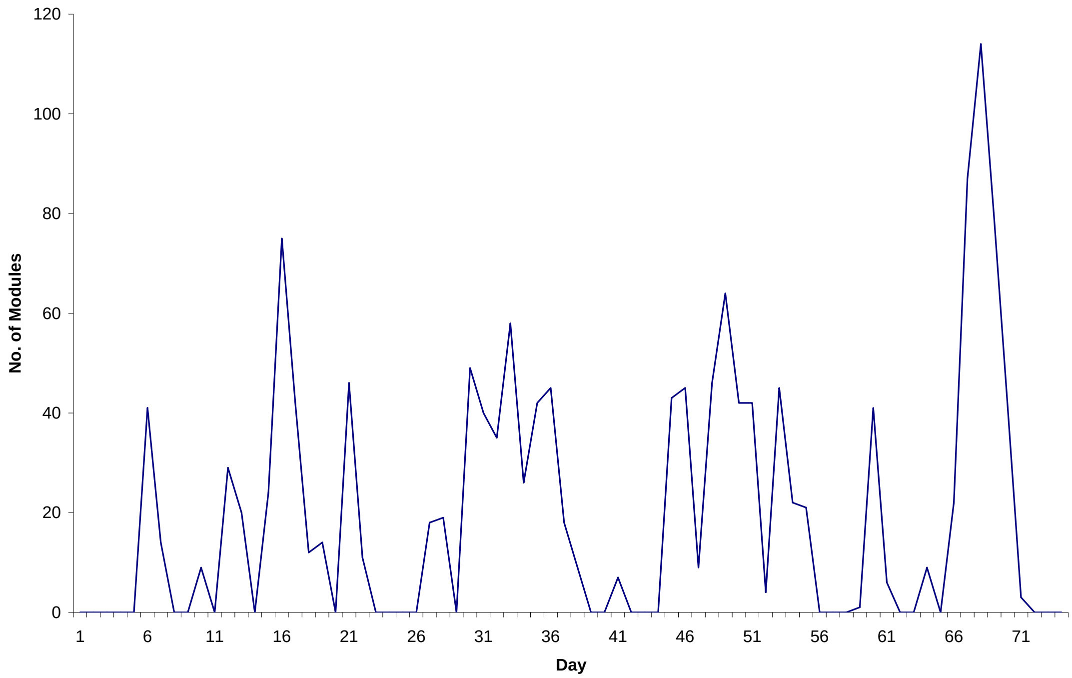


**Figure 4.7 No. of Modules waiting in the fields to be hauled (end of workday) 400*Beta [3.6, 11.5] (Day 0 = 10/1/2001) , from replication 5**

Figure 4.8 represents the number of modules in gin storage waiting to be processed by the gin. The gin does not start ginning at day zero. Ginning starts after the inventory level reaches 100 modules. In this particular simulation run (normal with five trucks), the gin started on day eight (Figure 4.6). During the day, the inventory starts to increase each time the trucks bring in modules and are represented by the jagged slope upwards. The corresponding decrease in inventory level due to the gin consuming this inventory is low and not clearly visible. After the trucks stop for the day or after all modules were transported, there are no new additions to the inventory and the inventory level decrease due to gin utilization is clearly visible. The downward slope represents this decrease in inventory at the gin. The flat lines represent days in which no ginning took place as the inventory level was below 100 modules.

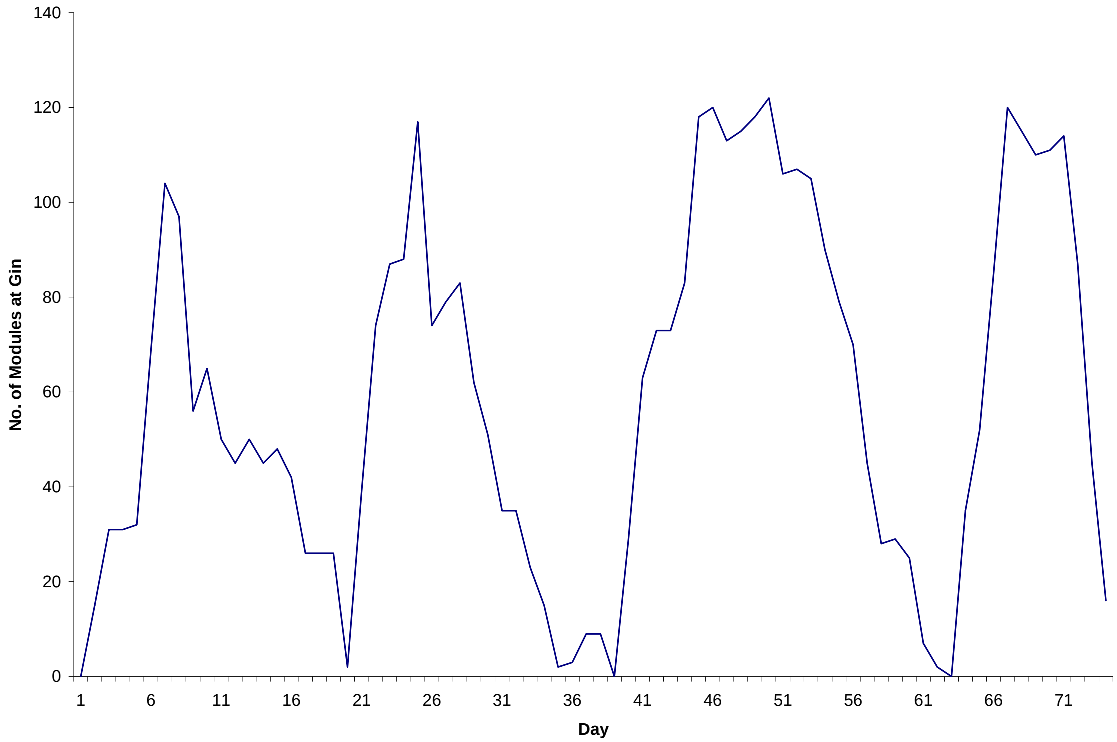


**Figure 4.8 Number of Modules waiting in gin storage to be ginned 400*Beta [3.6, 11.5] (Day 0 = 10/1/2001) , from replication 5**

## *4.6 Knapsack Formulations*

Figure 4.6 shows long periods of time when there were no modules to be hauled from the fields. All five module haulers remain idle during this time. This bottleneck should not exist in a biomass transportation system. To understand the effect of a process without this bottleneck, a knapsack model (Bazaraa et al., 1990) was constructed and solved to optimality. The model assumed that all 2,000 modules were available for pickup at the beginning of ginning season (t = 0). The optimal transportation schedule and minimum number of day module haulers need to move all 2,000 modules into gin storage was calculated.

Variables Used:

$y_i$ = 1 , if truck is scheduled to haul load on day i

= 0 otherwise

n = total number of modules

$w_j$ = Travel time to pick up module j, j = 1..n

$x_{ij}$ = 1, if module i is picked up on day j

= 0, otherwise

C = Total time available on any given day for hauling modules

= 600 min/day

Objective function: Min $\sum_{j=1}^{n} y_i$

The objective function is to minimize the total number of days that trucks are scheduled to move modules from the fields to the gin.

Constraints:

1. $\sum_{j=1}^{n} w_i x_{ij} \leq C y_i$, i = 1..n

This constraint forces total travel time for any day by the truck be less than or equal to 600 min if a truck is being used for that day, or equal to zero min if no truck is scheduled for that day.

2. $\sum_{j=1}^{n} x_{ij} = 1$, j = 1..n

This constraint forces each module to be transported from the field to the gin exactly once.

3. $x_{ij} \in \{0,1\}$, i = 1..n, j = 1..n

This constraint is used to define this variable as binary

4. $y_i \in \{0,1\}$, i = 1..n

This particular model was constructed for one single truck. Since all five trucks are identical, the results for one truck can be used to construct optimal solution for any number of trucks. Vector $x_i$ will provide a list of all modules transported on day j, with

$x_{ij}w_j$ providing total travel time on any given day. This model was coded in AMPL/CPLEX (Bell Laboratories, 2003; ILOG, 2004) and run on an IBM machine. Fifty-four days were needed to transport all 2,000 modules from the fields to the gin in this model when compared to 74 days needed by the simulation model.

## *4.7 Greedy Transportation Strategies*

In a "greedy" algorithm, the algorithm chooses the locally optimum choice at each stage with the hope of finding the global optimum (Cormen, 2001). In this management policy, the algorithm tries to satisfy inventory demand at the gin by moving modules that have lowest cycle time i.e., greedily. The average number of modules a truck can deliver to the gin per day is approximately six. With all five trucks operating, the gin receives approximately 30 to 35 modules-per-day, depending on travel times. The gin, on the other hand, consumes around 45 modules-per-day. This mismatch between these two processes will quickly deplete the 100 module buffer the gin started out with, and the buffer will eventually reach zero. To reduce the chances of this happening, the threshold limit at which the gin starts operating was increased. The cotton ginning model was simulated with 100, 200, 300, 400 and 500 module threshold for start of ginning process. Of these different threshold levels, only 500 modules in initial storage operated the gin full time without stopping. Five hundred modules are around 25% of the total number of modules processed per season. Maintaining such a large inventory, although feasible, is not cheap. One way to reduce this inventory storage requirement is by using a greedy algorithm based transport strategy.

### *4.7.1 Greedy Algorithm, Smallest First*

In a greedy transportation plan, modules with the smallest travel times are transported first. This allows the gin to reach its operating threshold of 100 modules and maintain that level early in the season without much trouble. Eventually, the inventory level drops off as modules have longer transport time and the gin runs out of modules. But this event will occur during the latter part of the season, where the management can adopt a better policy to reduce gin shutdown (for example, operate gin for 12 hrs per day instead of 24 hrs). The simulation model was modified to remove event "MCall" and was replaced by a dataset containing modules, sorted in ascending order by their travel times. Each time a truck was scheduled, the module with the smallest travel time was assigned to the truck.

Figure 4.9 shows a graph of inventory level at the gin for a greedy transportation plan. As expected, the number of modules rises very quickly and the gin operates at 100% efficiency. This caused the maximum inventory level to increase by 130 modules. This additional inventory at the plant was not a significant problem as the Gin's storage capacity was in excess of 500 modules. During the end of processing season, the gin's inventory reaches zero, twice. Both times, the gin waits till inventory is built up to 100 modules before it starts ginning again. This corresponded to stoppage times of 5 and 7 days, respectively. Figure 4.10 shows the number of modules ginned when using this policy.

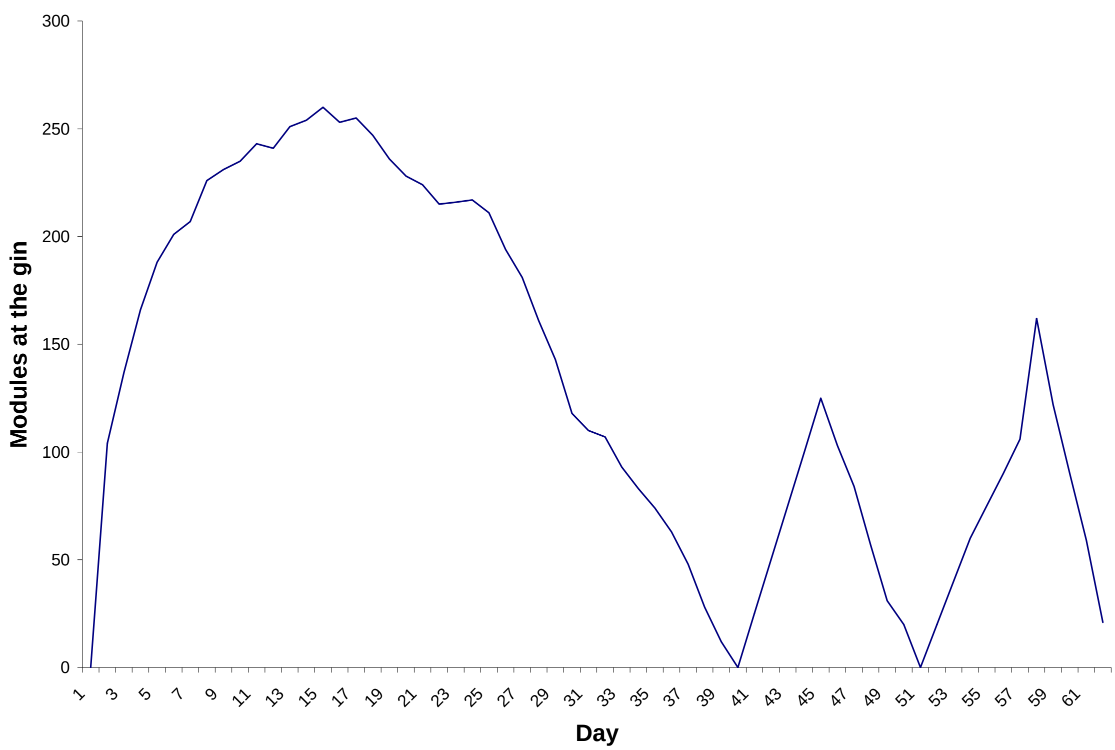


**Figure 4.9 Module inventory level at the Gin, Greedy Policy "Shortest First"**

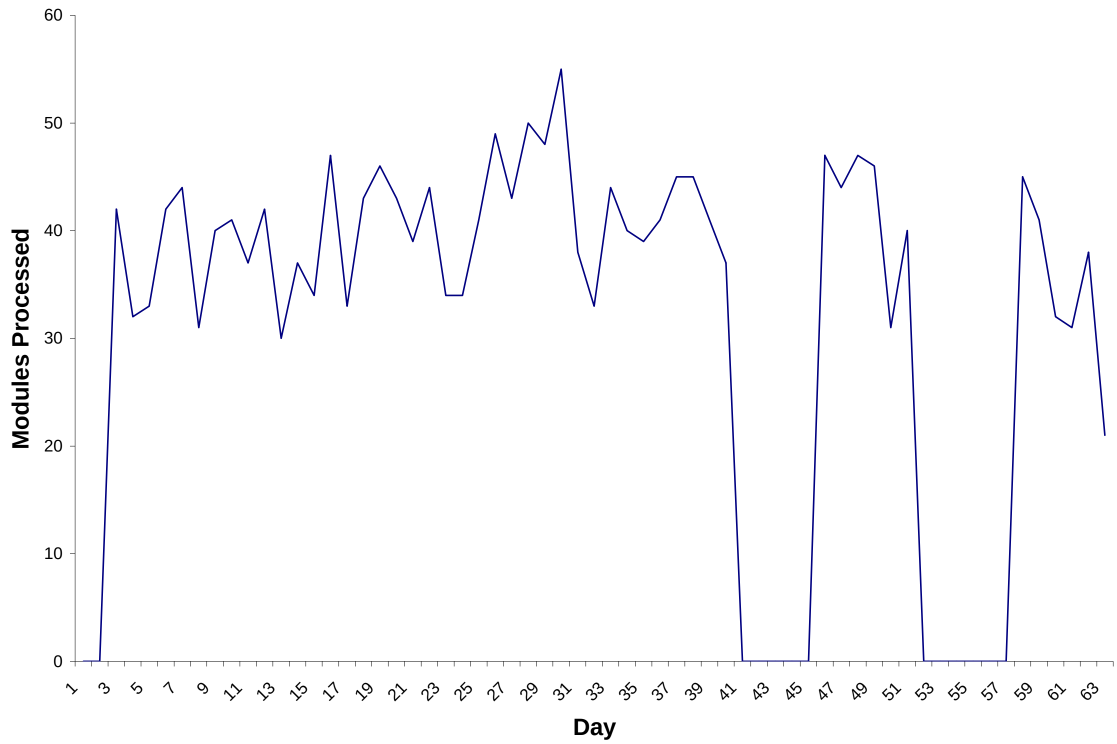


**Figure 4.10 Number of modules processed by the gin on any given day, "Shortest first" policy**

### *4.7.2 Greedy Algorithm, Largest First, Smallest Second*

An alternate greedy algorithm, in which modules with the largest travel time were moved first to satisfy some part of the gin's initial inventory, was also simulated. That is, if the ginning threshold is set at 250 modules, move those 100 modules with the largest travel time first and then start moving based on "Smallest First" policy. It was expected that by rescheduling the smaller travel time module pickups later in the simulation run, the transportation system of the gin should not have any problems transporting enough modules to keep the inventory level above zero. The simulation model's dataset was rearranged such that the initial 100 modules were modules with highest travel times and the rest of the order was left unchanged "Smallest First" model.

Figure 4.11 shows the gin's inventory level when the threshold was moved to 250 modules and the greedy policy modified. Clearly, the gin has sufficient modules to operate at 100%. Figure 4.12 shows the number of modules ginned per day using this policy. The gin starts processing modules later than under any other management policy simulated finishes ginning at the same time as "Smallest First" management policy.

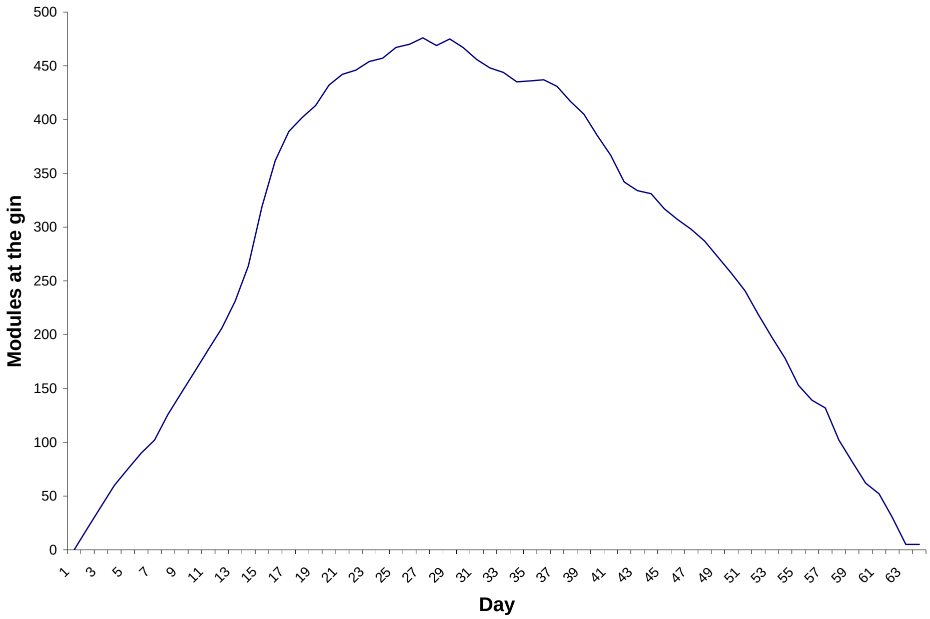


**Figure 4.11 Module inventory level at the gin, "longest first, shortest second" policy**

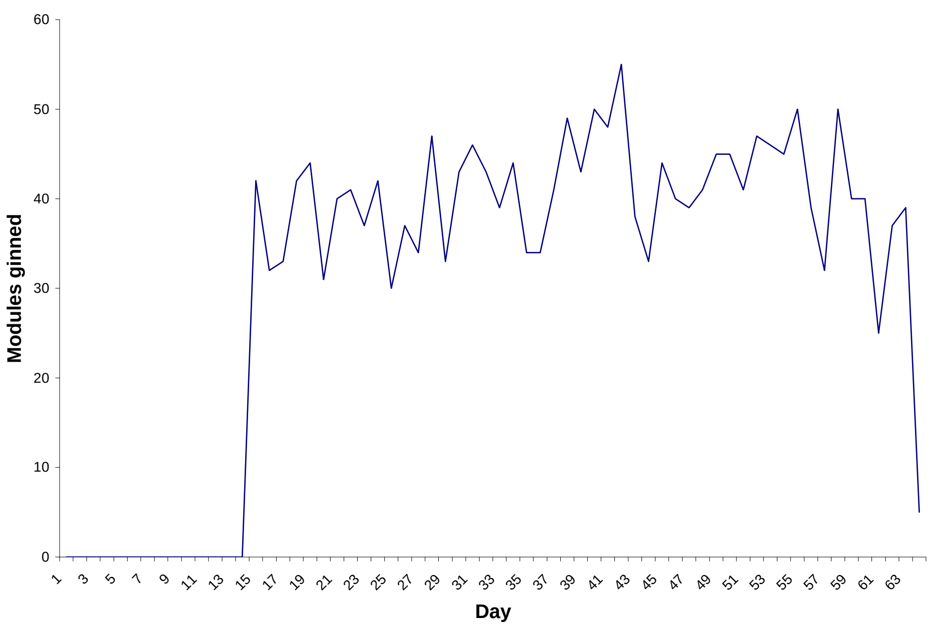


**Figure 4.12 . Number of modules processed by the gin on any given day under "longest first, shortest second" policy**

## 4.8 Cotton Logistics correlated with Biomass Logistics:

Biomass logistics involves hauling baled grasses from on-farm storage to a central plant which uses several components or subsystems that are similar to the transportation system for cotton modules. A concept has been proposed [Cundiff, 2004] whereby multiple round bales of grass hay are compacted into a module, which becomes the handling/transportation unit. The round bales are modularized to produce a package that achieves the same handling advantages as the cotton module. But there are four key differences that need to be considered when drawing inferences between the two systems.

1. In cotton logistics, one cotton module is considered as one unit load and each truck can transport one unit. So one module and one truck can be used interchangeably. In the case of biomass, there may be more than one module loaded onto a single truck and therefore one unit load is not the same as seen in cotton logistics. For simulating biomass transport, it will suffice to model one truckload as one unit and not consider individual bales of hay except during load/unload. Current biomass logistic systems load/unload bales individually. This process is cumbersome and current research is being conducted to reduce the load/unload times. The proposed concepts call for the multi-bale module to be loaded and ready for the truck when it arrives at the on-farm storage site. The goal is to load the truck in 10 min. This compares with a load/unload time of less than 5 min for a cotton module. The cotton gin data includes this load/unload time in the truck travel time. No effort was made to separate on-road time and load/unload time because this step takes so little time and doesn't affect simulation results in any significant way. But, the load/unload time is significant in biomass logistics due to large volume of trucks and could be a potential bottleneck.

2. Current simulation of cotton logistics shows that when operating under ideal conditions, truck utilization and therefore gin utilization are constrained by module call-in rates (FIFO strategy), as this dictates availability of modules to be hauled. Figure 4.7 shows that the hauling operation "catches-up" with modules waiting to be hauled and no modules are available to be transported. In a biomass system, the amount of biomass

accumulated in the on-farm storage will be known and hauling optimization can be achieved. The hauling operation does not "catch-up" with multi-bale modules waiting to be hauled and therefore, trucks can be operated at maximum utilization. This characteristic may help schedule trucks efficiently and has to be explored when simulating biomass systems.

3. This simulation model assumes that there are no limitations on the number of modules that can be stored at the gin. When considering a biomass system, there are practical and economic limits on the size of storage at the conversion plant, which will dictate maximum storage (inventory) level. The advantages of "just-in-time" feedstock delivery are substantial.

4. A cotton gin is a mechanical process in that it can be started and stopped without significant effort or economic penalty. A biomass conversion plant is a chemical process. The cost penalty for starting and stopping the production flow is much greater. Therefore the penalty for running out of feedstock is much higher for a biomass plant than a cotton gin.

## 4.9 Conclusion

A case study was completed for a gin in Emporia, VA with five trucks, the truck utilization factor was 77% and the gin utilization factor was 69%. The gin operated for 80 days during a season with normal truck travel times. The season length increased to 83 days when the truck travel times were increased by 10 and 20 min. The gin's utilization factor also decreased from 69% to 66%. The truck utilization factor increased from 77% to 80% and 89% with increasing truck travel times. Cost figures from the gin are not available, but the cost of operating the gin is believed to be significantly greater than the cost to operate the fleet of trucks. Therefore, a reduction of truck fleet was not recommended.

The current gin logistics are constrained by the FIFO policy and there is limited opportunity to increase truck utilization percentages during the harvest season. If there was an opportunity to choose which modules to haul, then a knapsack model can be formulated and the solution would increase the truck utilization and reduce overall truck requirements.

Decreasing truck cycle time does not increase the truck utilization factor significantly, since module call-in rates currently constrain truck utilization rates. To achieve an increase in the utilization factor, more modules have to be available. This means that the customer base has to be increased from current levels or the gin waits until sufficient modules are available before hauling starts. The effect of such an increase on ginning operations along with impact on processed cotton bale price needs to be explored.

The modified greedy algorithm provided better gin utilization factor than any other management plan. The “smallest first” greedy algorithm reduced the ginning season from 80 days to 61 days. This also increased the maximum number of modules stored at the gin from 120 to 260. This increase was not sufficient to keep the gin running continuously and the gin stopped twice in during the season. The “longest first, shortest second” further reduced the ginning season to 51 days. This modified greedy algorithm also reduced the threshold level from 500 to 250 to operate the gin continuously. The maximum number of modules stored at the plant increased to 470. This algorithm allowed the gin to operate continuously for the season without any stoppage. There are several components or subsystems of the transportation system for a cotton gin that a biomass system can envision.  While differences are evident, the system analysis can be useful for determining operating parameters for potential biomass transportation systems.

# Chapter 5 – Facility Location and Production Area Analysis

## 5.1 Introduction

The location of the processing plant in a road network will determine the travel time of trucks transporting biomass from a set of satellite storage locations to the plant. This travel time, along with loader availability, determines the total number of trips a truck can make from a satellite storage location (SSL) on any given day and controls the total number of trucks needed for the plant to operate at capacity. An arbitrary selection of this location may place the plant at a location with large cumulative travel time, thereby increasing the number of trucks needed.

Once built, the plant and its support systems cannot be moved to a newer location without a significant cost penalty. This sunk cost may not be recoverable and can adversely affect the economic feasibility of the plant. These factors necessitates that the plant location should be picked to not only minimize total travel time, but also be in a position to use the same location without significant procurement problems in future.

## 5.2 System Description

Cundiff et al. (2006) describes a system in which biomass, once harvested, is baled into 1.5m round bales. These bales are then picked up by specialized self-loading trucks, known as bale wagons. Bale wagons can load/unload 10 bales at a time from the field and move them to intermediate storage sites known as satellite storage location or SSL. Each SSL has a 3.2 km (2 mile) procurement region from which it accepts baled biomass. This limit on procurement region was introduced to reduce bale wagon's travel distance, as they are limited to speeds of less than 32km/h (20 mph).

These SSLs are located with direct road access which can handle a normal semi-truck under all weather conditions without causing trafficability problems. Loaders at these SSLs load one truck at a time and are designed to fully load a truck with 32 bales every 30 min. Once all bales at a SSL are loaded, these loaders move on to the next location.

There will be several such loaders operating in a given region to satisfy demand at the processing plant and the order in which these SSLs are visited will be determined by the management policy the plant decides to use.

### *5.3 Data Collection and Preprocessing*

Two separate production regions in Virginia were analyzed as potential procurement regions. Each group had seven counties with varying production areas. One production region was located in Southern Piedmont region of Virginia [henceforth referred to as SPV] and consisted of Henry, Franklin, Pittysylvania, Halifax, Bedford, Charlotte and Campbell counties. The other production region was located in region was located in Northern Piedmont region of Virginia [henceforth referred to as NPV] and consisted of Madison, Orange, Albermarle, Spotsylvania, Fluvanna, Greene and Louisa counties. These counties have some of the largest hay producing regions in Virginia and were selected based on that attribute alone. Figure 5.1 shows the location of these two regions. No effort was made to equalize the production areas between these two regions.

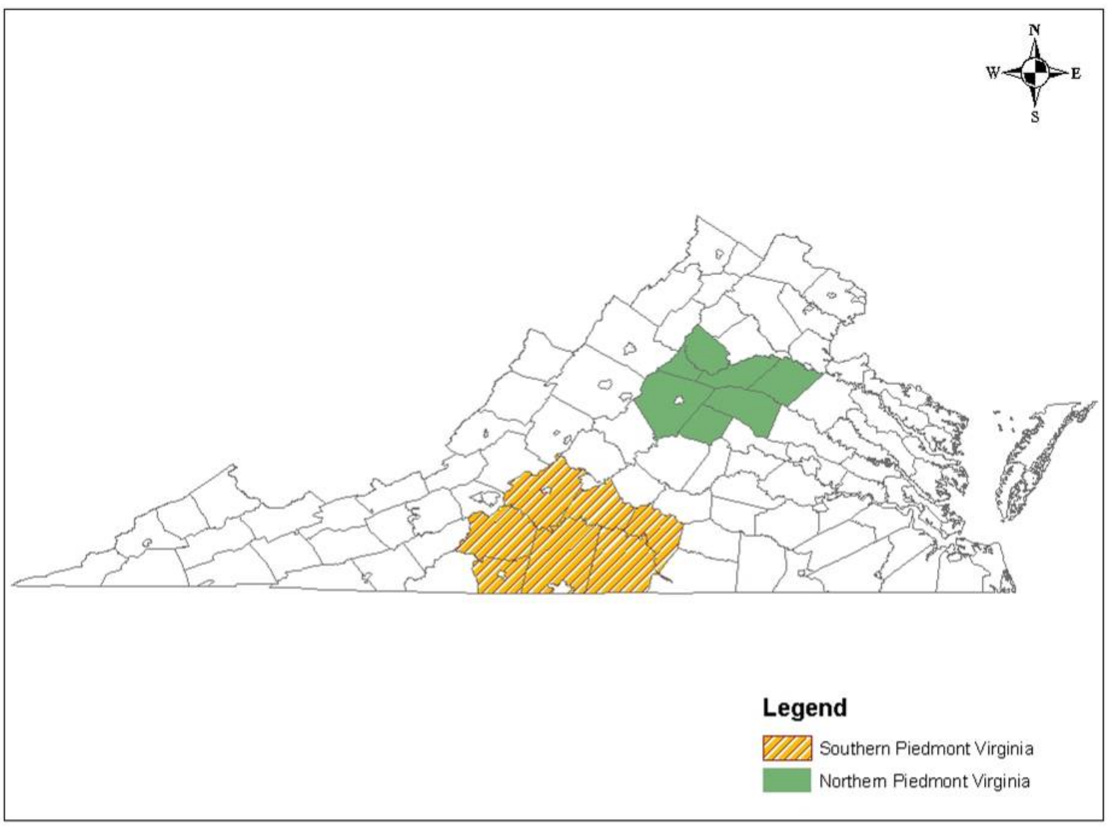


**Figure 5.1 NPV and SPV regions**

National Land Use Classification Data (NLCD) from US Geographic Survey's seamless data server was used as a basis for production area analysis (USGS, 2000). Cartographic county boundary shapes from GIS server at Virginia Tech (Virginia Tech, 1990) was merged by region and used to "cut" these NLCD datasets for each region. Tiger 2000® dataset from ESRI (2000) provided rail and road network information for these counties. All datasets were assigned NAD 83 coordinate system and projected into UTM zone 17. A raster cell size of 30m was assigned to all conversion and calculations. Merged county boundaries were used as "extent" in all raster calculations.

## 5.4 Production Area Analysis

The county boundary shapefile was merged to form an outline for SPV and NPV regions. These shapefile was then used to resample NLCD dataset into 30m cells. Since NLCD dataset uses integer values to denote land use type, mathematical interpolation techniques would produce cell values that do not have any physical meaning. To avoid this pitfall, nearest neighbor technique was used. By using the outline for SPV (or NPV) region as extent in this step, the dataset size was reduced significantly, improving processing times.

A cell value of 81 in a NLCD raster corresponds to pasture. Raster calculator was used to convert all cells with a value 81 into cells with value 1. All other cells were converted into "null." This provided a clean raster dataset for SPV and NPV regions with only pasture cells. Figure 5.2 and Figure 5.3 show the converted dataset for SPV and NPV regions respectively. Dark areas represent regions with high pasture cells and lighter regions represent regions with little or no pasture cells. It can be observed that there are some areas relatively clear of pasture cells. Appendix A5, Table A5.2, Table A5.3, and Table A5.4 list the SSLs and the corresponding pasture land available in each SSLs procurement region for 50%, 45%, and 40% land use rates.

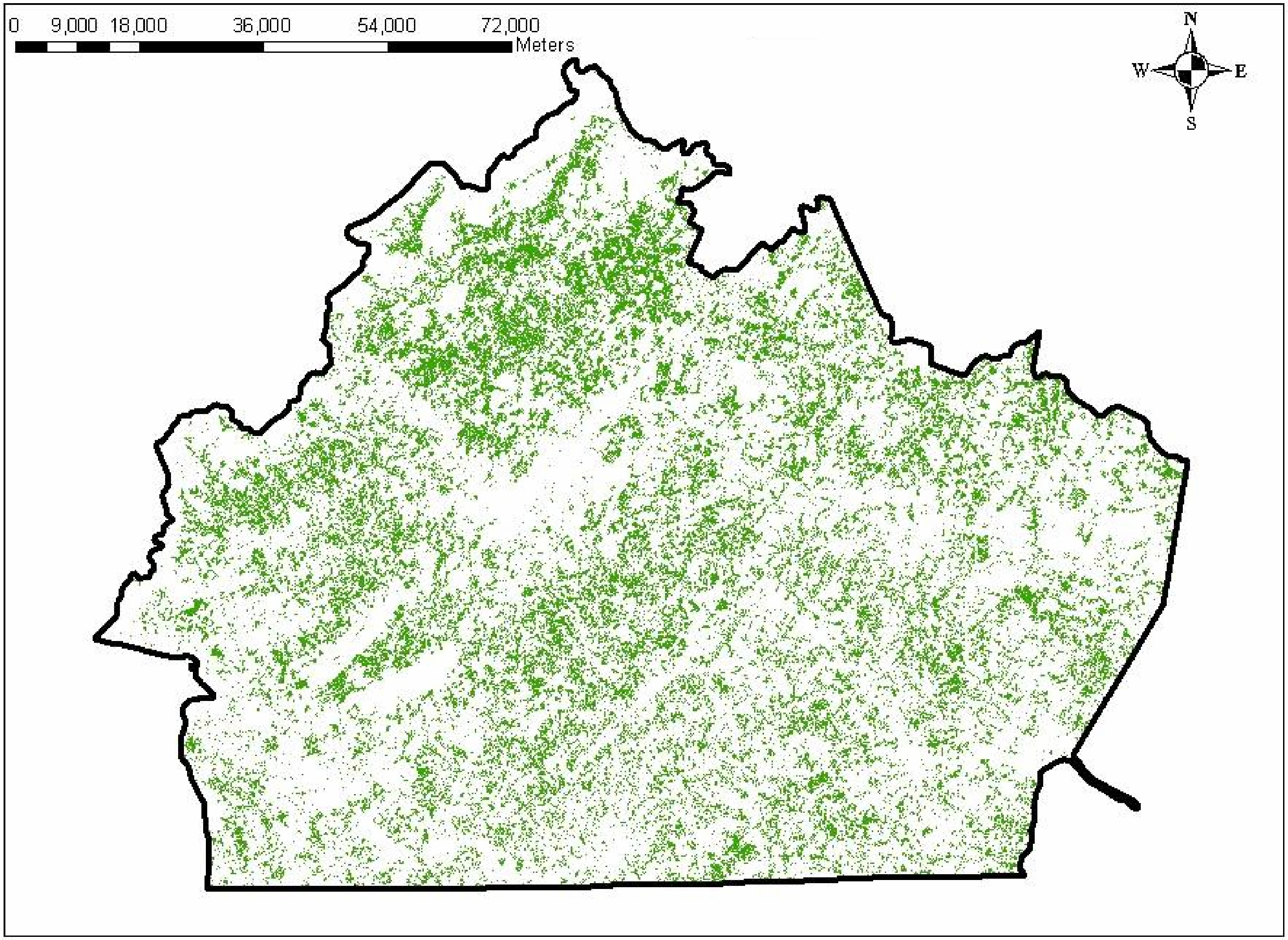


**Figure 5.2 SPV Pasture cells**

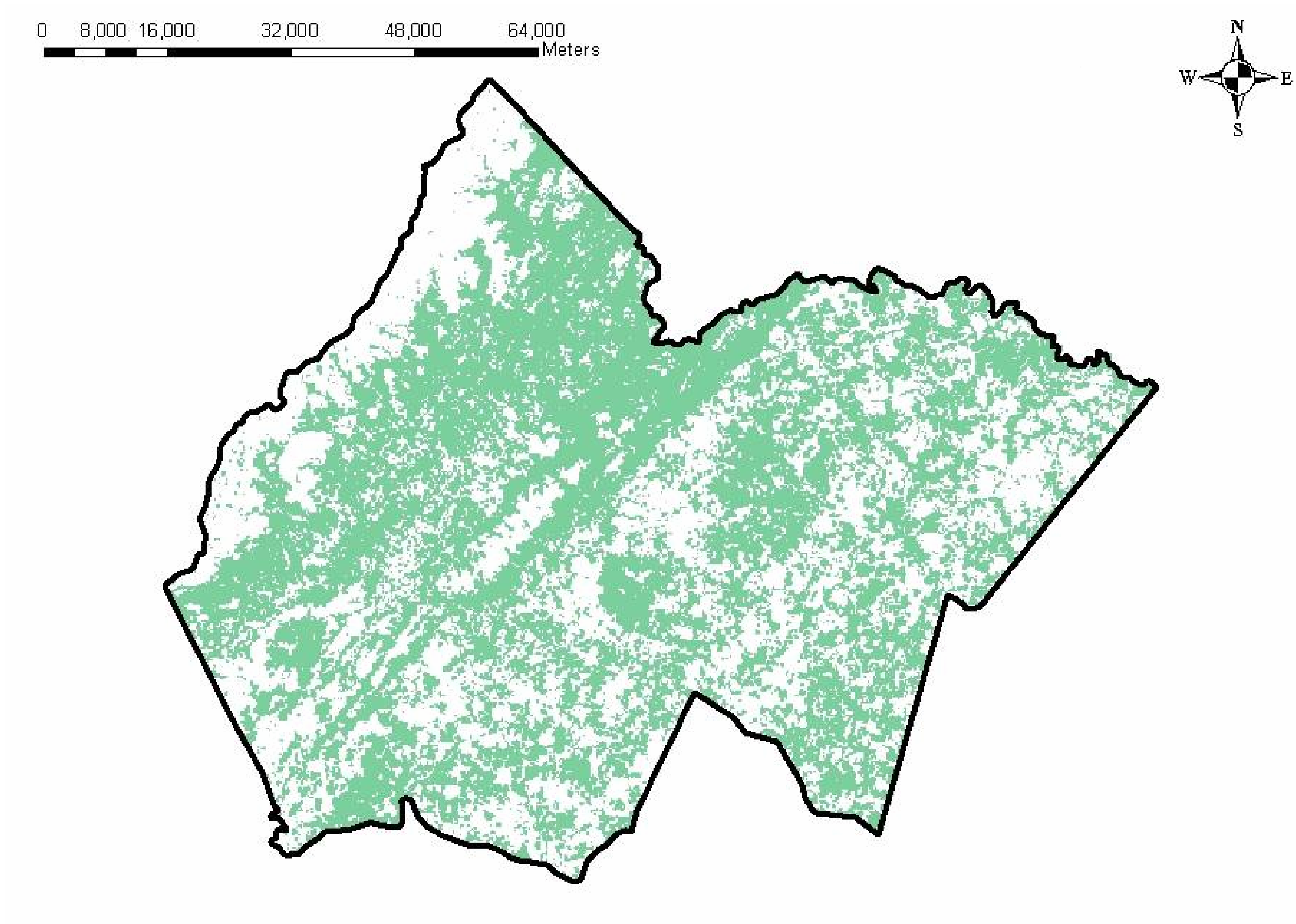


**Figure 5.3 NPV pasture cells**

## 5.5 Satellite Storage Locations

Circles with 3.2 km (2 mile) radii were placed in areas with high concentration of pasture cells from the previous step. It was assumed that only material from within this 3.2 km production area will flow into the SSL located within that circle. This limit was a requirement for the efficient operation of bale wagons during their post harvest transportation of bales from the fields.

Each production circle was placed such that the area within its area had enough raw material to keep a loader fully occupied for one work week. At 30 min per load and 20 loads per day, it translates to 100 loads per SSL. This was done to reduce the number of moves a loader has to make in a week. Areas that did not meet this constraint were removed and reallocated. This load rate of 20/day is not practically feasible due to truck non availability, machine breakdown and other factors. Even with this high cutoff, there were sufficient SSLs to satisfy demand at the processing plant. Figure 5.4 and Figure 5.5 show the SSL production circles located in SPV and NPV regions respectively.

## 5.6 Road Network

ArcMap's geoprocessing wizard was used to merge all individual county road shapefiles in SPV and NPV regions. Figure 5.6 and Figure 5.7 show these merged files for SPV and NPV regions respectively. These merged shapefiles contain detailed information including road type and length. The road type information is contained in census feature class code or CFCC field. CFCC uses alphanumeric code to identify and classify each road segment into several categories (US Census Bureau, 2000). For this study, these classifications were grouped into three groups, namely, primary, secondary and tertiary roads.

The author observed truck travel speeds on different type of roads in southern Virginia as part of cotton module logistic study (Table 5.1). It was assumed that the trucks in this system will operate under similar speeds and those values were used in this analysis.

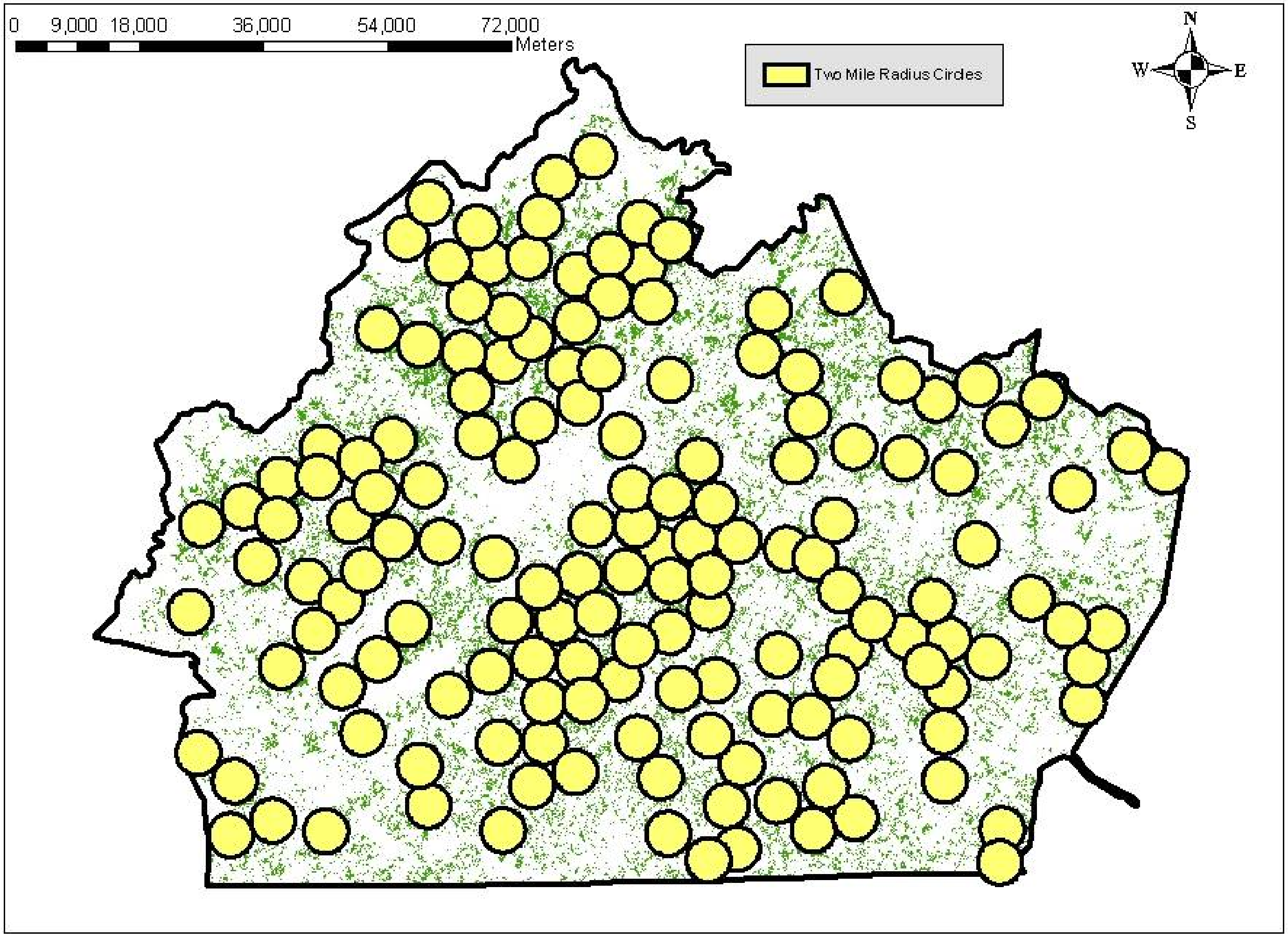


**Figure 5.4 Production circles in SPV region**

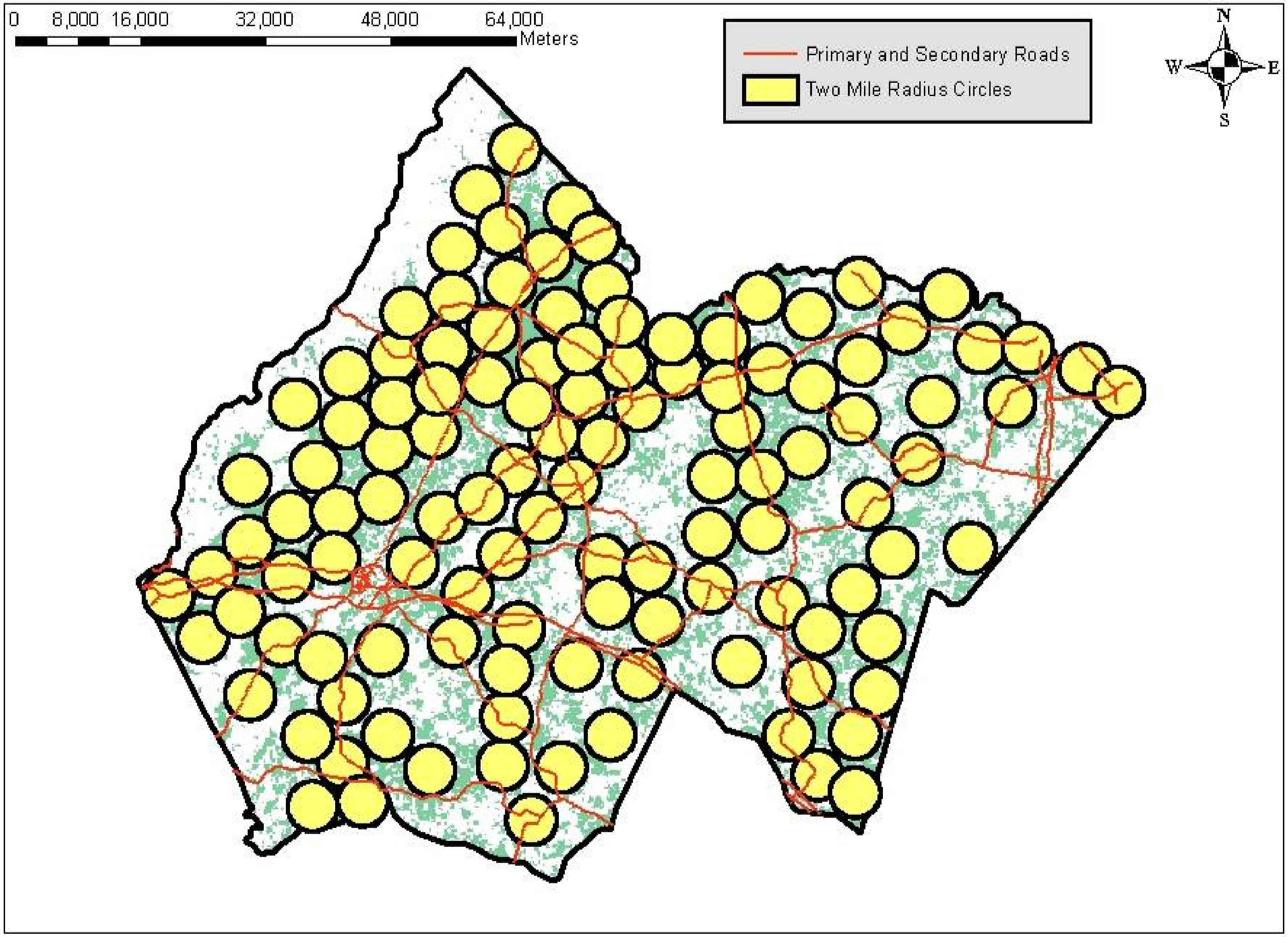


**Figure 5.5 Production circles in NPV region**

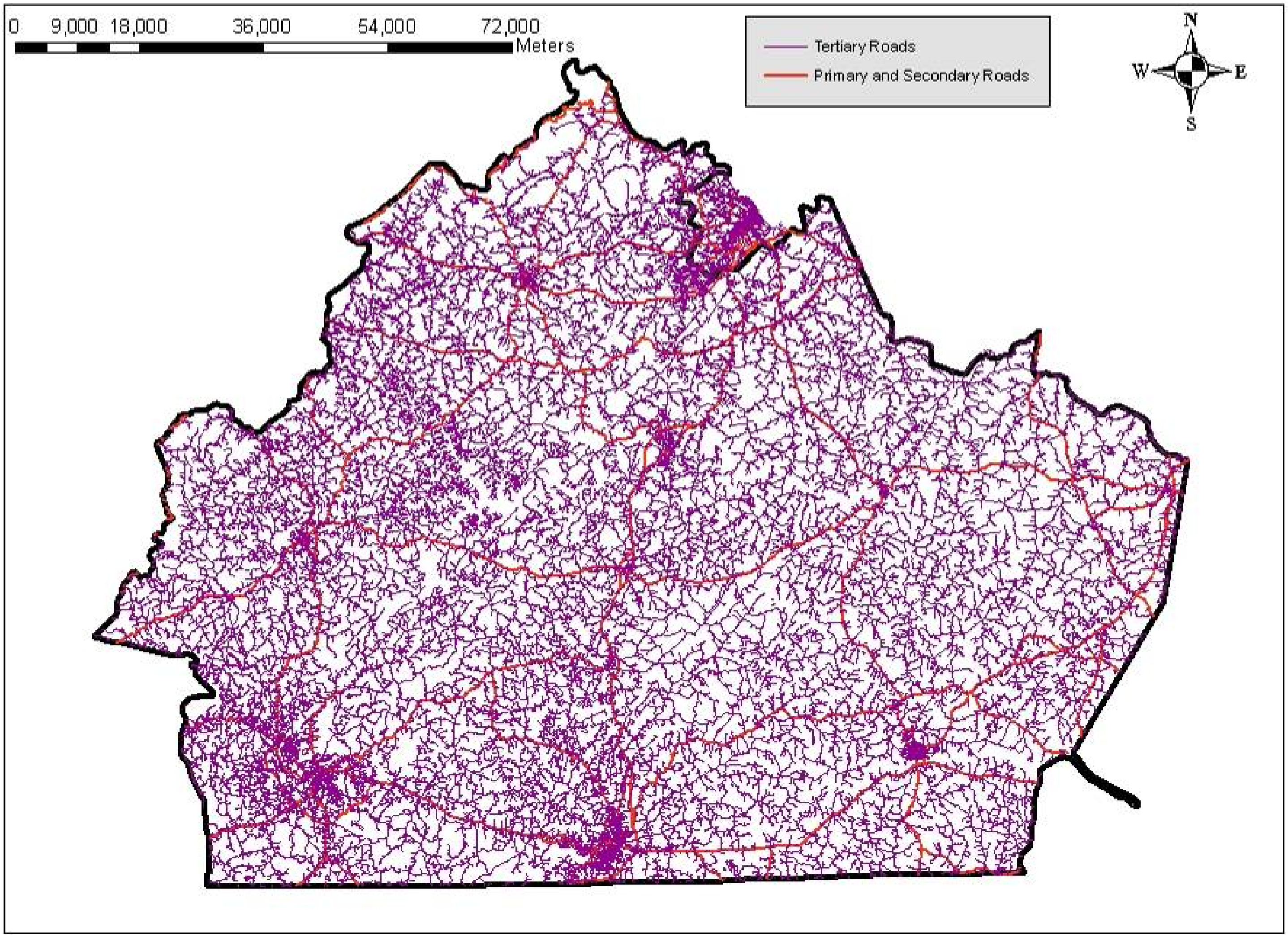


**Figure 5.6 Road network, SPV region**

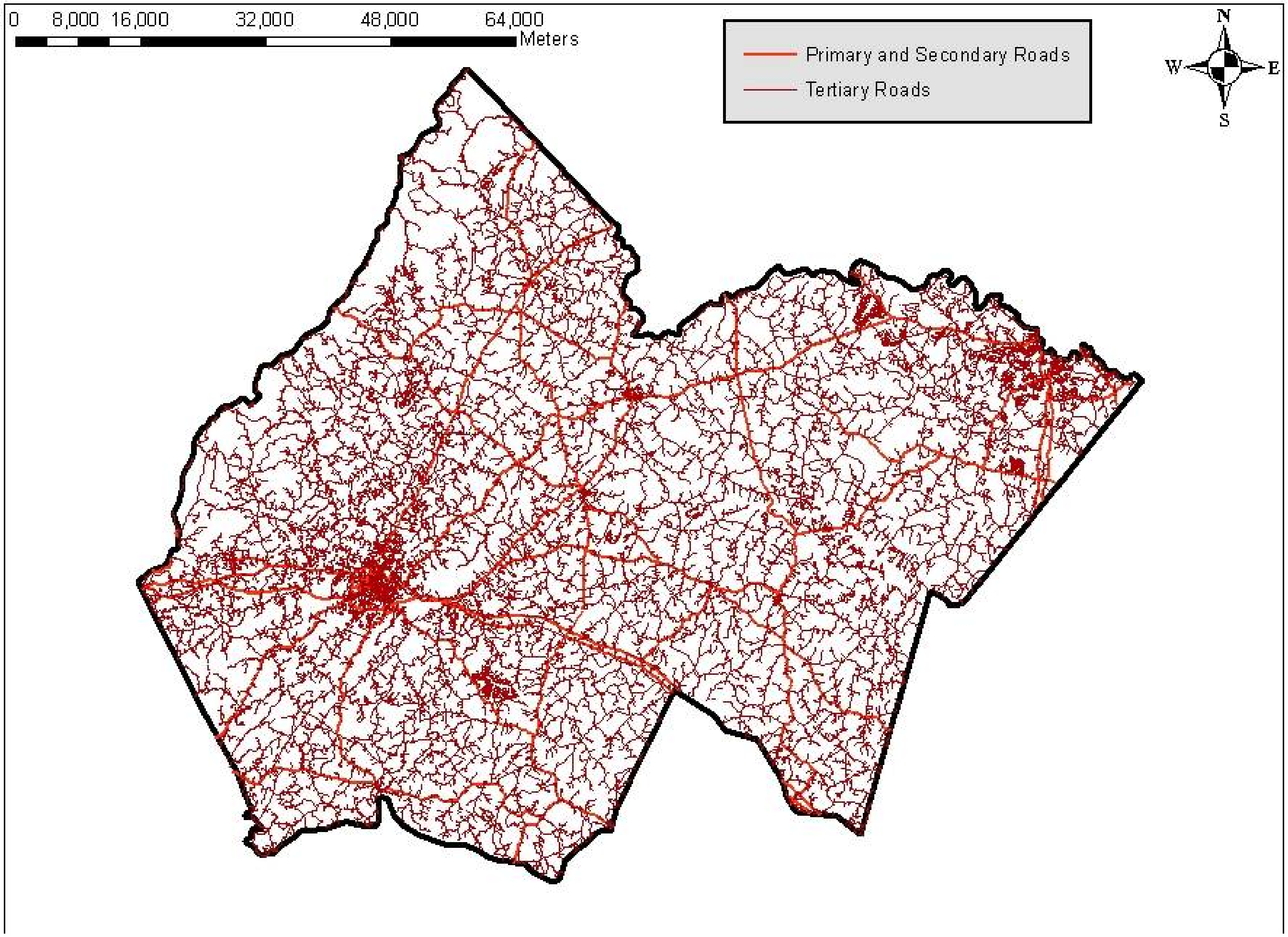


**Figure 5.7 Road network, NPV region**

Table 5.1 shows these three road groups, their corresponding CFCC equivalents and road speeds assumed in this study. ArcCatalog (ESRI, 2005) was used to add three additional fields to this shape file, namely, speed (m/s), length (m) and weight (sec). The roads were separated into their corresponding groups and speeds were assigned to them based on road type. The speed in m/s was inverted to calculate a "weight" field. This weight is physically equivalent to the number of seconds a truck takes to travel one meter when traveling at average speed for a road group. The weight field is used in optimal route calculations.

This modified shapefile was then converted into a 30m raster, with weight filed as cell value. This raster served as "cost" for truck travel through road network. Each SSL in a procurement circle needs to be on the road network for this analysis to run successfully. Otherwise, the GIS program will not see a path to a SSL and will eliminate it from analysis. Therefore, the SSL locations were placed on the road network manually using ArcMap's (ESRI, 2005) editor and converted into a raster. Figure 5.8 and Figure 5.9 show the location of SSLs in SPV and NPV region, respectively.

**Table 5.1 CFCC fields and road types**

| ***Road Type*** | ***CFCC*** | ***Speed in m/s*** | ***Speed in mph*** |
|---|---|---|---|
| Primary highways with limited access | A11 to A28 | 24.6 | 55 |
| Secondary and connecting roads | A31 to A38 | 17.9 | 40 |
| Tertiary roads (Local, neighboring and rural roads) | A41 to A48 | 13.4 | 30 |

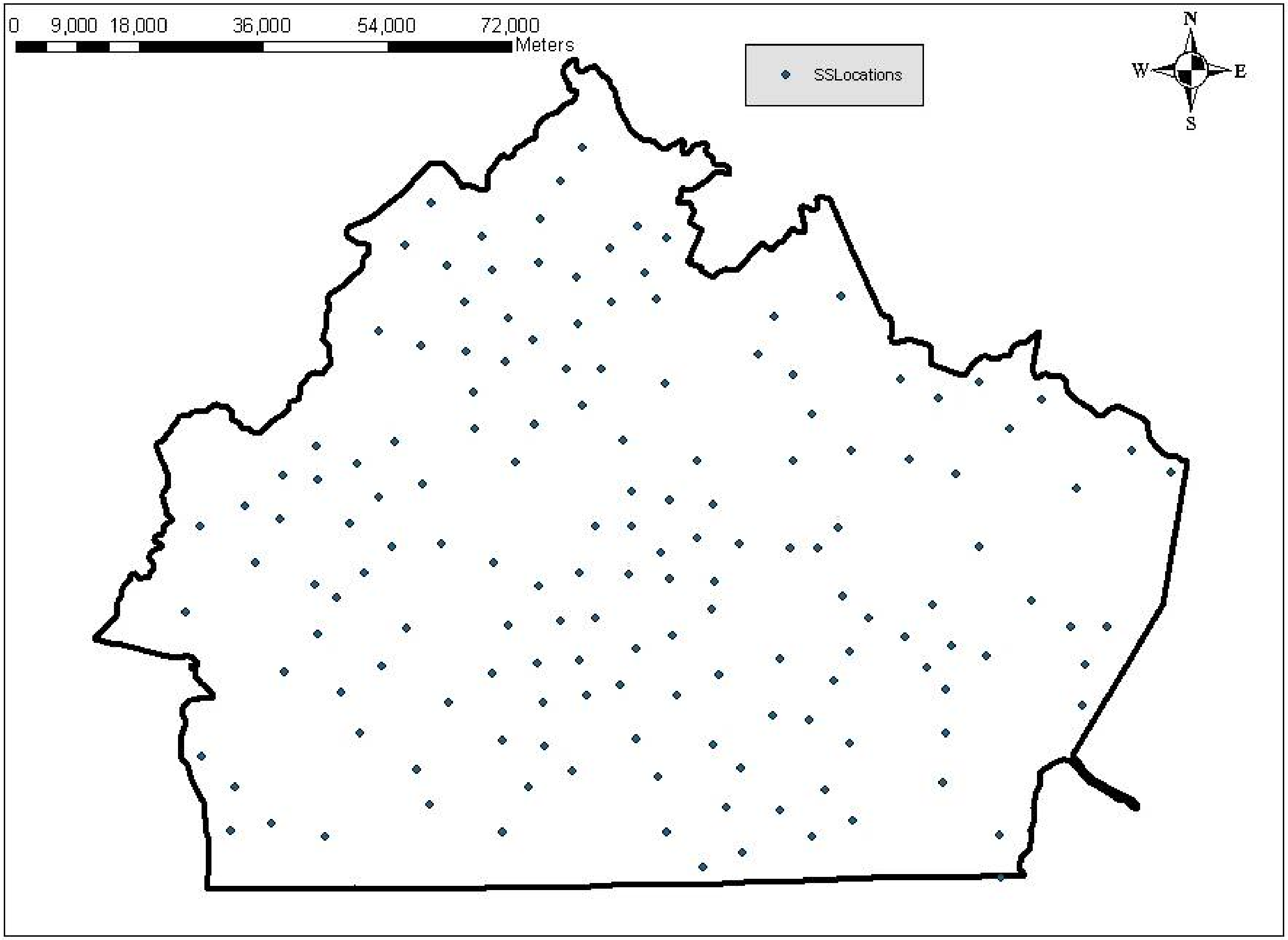


**Figure 5.8 Satellite storage locations in SPV region**

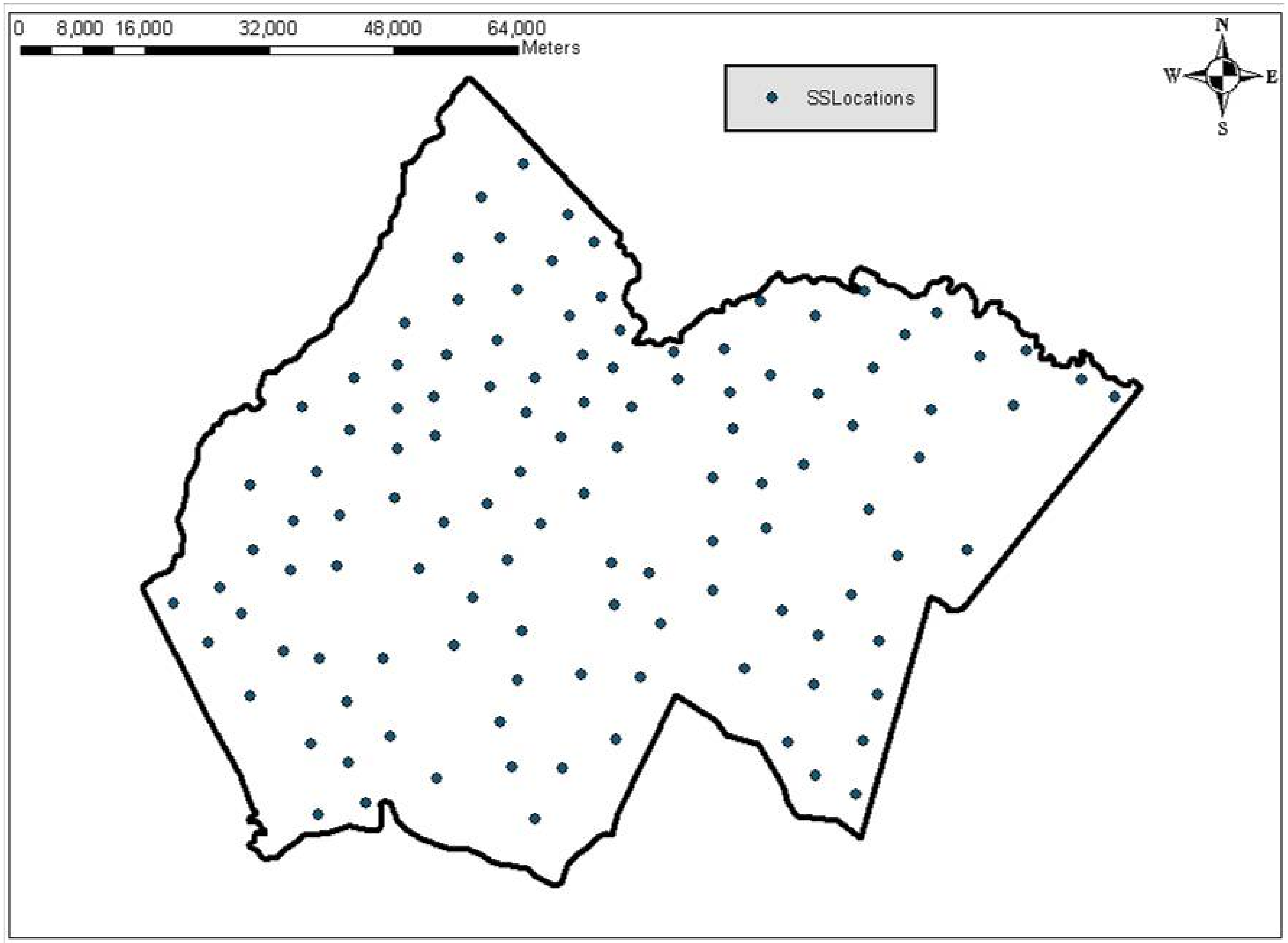


**Figure 5.9 Satellite storage locations in SPV region**

## 5.7 Optimal Facility Location

The goal of this analysis is to determine a plant location that will minimize travel time to all SSLs a particular region. Husdal (2000) used a raster based methodology to determine lowest "cost" to reach any given cell in a raster (refer to section 3.5.2 for more details). Mathematically, the problem can be expressed as

$$\text{Select Min } \left\{ \sum_{i=1}^{n} X_{ij}, \ j = 1..m \right\}$$

where

n = total number of cells in a raster

m = total number of SSLs in a raster

$X_{ij}$ = travel time from cell i to SSL j

In a typical facility location problem, there are a very small number of potential locations that are explored to find optimal location. In this raster methodology, every cell in the raster becomes a potential location. This increases the computational penalty for solving the problem, but with available computational power, this problem can be solved in a reasonable amount of time.

For each SSL, spatial analyst's Weighted Distance function was used to calculate travel time from that SSL to every other cell in the region. The road cost raster computed in previous step served as the weight function. This process was repeated for all remaining SSLs and the resulting rasters were added together. Each of this final raster's cells contains the cumulative minimum travel time to reach all SSLs in the region from that cell. Isolating the cell with the minimum value and converting that cell into a shapefile produced the optimal location for the processing plant.

Once the optimal location for a region was identified, ArcMap's utility network was used to generate a vector based min travel time route to all SSL locations from the plant along with travel times. This has the added advantage of producing street names and distances, which could be used by a GPS system to accurately guide a truck to a SSL location.

## *5.8 Summary and Discussion*

The number of SSLs needed in a region to satisfy demand at the plant is a function of total land available for biomass production within a SSLs procurement region and land use rate. Increasing the land use rate increases the number of loads at a SSL. This increase in loads brings down the total number of SSLs needed in a region. In this analysis, 155 SSLs were needed in SPV region to satisfy plant demand. The NPV region had a higher concentration of pasture land and only needed 117 SSLs. The number of loads available at each SSL at 50%, 45%, and 40% land use rate was calculated. This information was used in the next step (Chapter 6) for generating schedules using various management strategies.

The location of the plant determines the travel time from the plant to a SSL. Since the number of trucks needed by a SSL is a function of travel time, building the plant at an optimal location will reduce the total number of trucks needed by the truck transportation system. The travel times were computed based on SSL locations and the optimal facility location was determined using a spatial technique. Figure 5.10 and Figure 5.11 shows the location of optimal facility location for SPV and NPV region, respectively.

The optimal location for SPV region is close to its geometric center. On the other hand, the optimal location for NPV region is significantly off its center. This is due to the fact that there were higher concentrations of pasture in one area (northwestern region), which acted to pull the optimal location towards itself. This agrees well with the intuitive conclusion that optimal facility should be closer to an area with higher raw material.

Figure 5.12 shows the travel times for all SSL locations in SPV and NPV region. The SPV region had an average truck travel time of 46.2 min and the maximum travel time was 84 min. The NPV region was smaller and the travel times reflected this. The average truck travel time was 34.6 min and the maximum travel time was 68 min.

Figure 5.13 and Figure 5.14 show the travel time contours for SPV and NPV region. As the figure shows, there were pockets with high travel time within lower contours. This is caused by tertiary roads due to their low speed rating. This information could be used to determine sub regions that have a relatively low transport cost and recruit farmers in that sub region to grow more biomass. With this information, a processing plant can target regions that have a low travel time and reduce its overall truck requirement.

The number of trucks each individual SSL needs is fixed once the location of the plant is determined. But, the total number of trucks needed per day and the maximum number of trucks needed by the system depends on the SSLs being used on any given day. This parameter can be reduced by controlling the order in which the SSLs are visited during a 6 month season. So, the next step in this analysis was to implement management policies to generate the SSL scheduling order. It is expected that the SSLs in NPV region and SPV region will behave in similar fashion when these management policies are used. It was therefore decided to use SPV region for the next steps in this study.

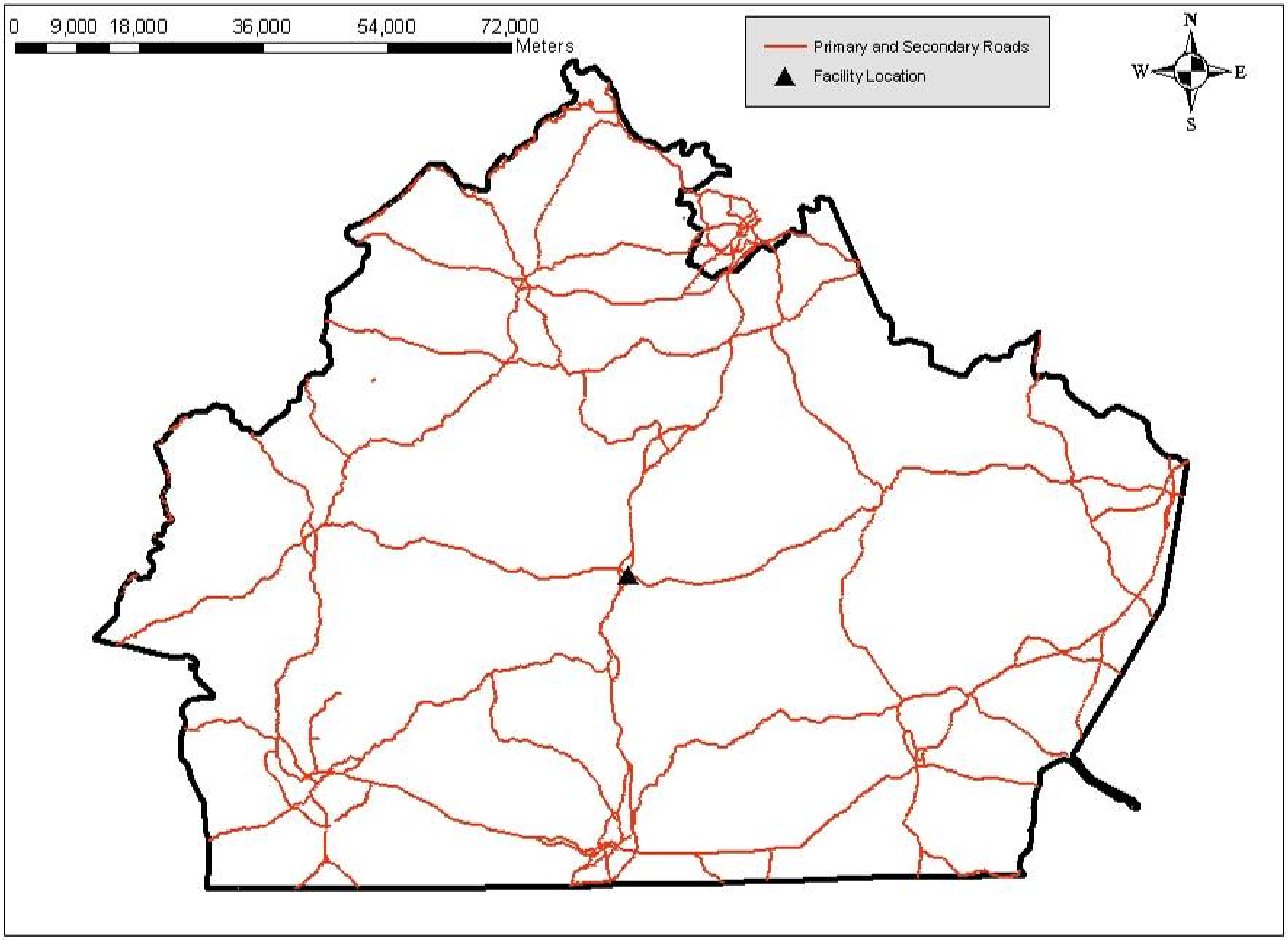


**Figure 5.10 Optimal facility location, SPV region**

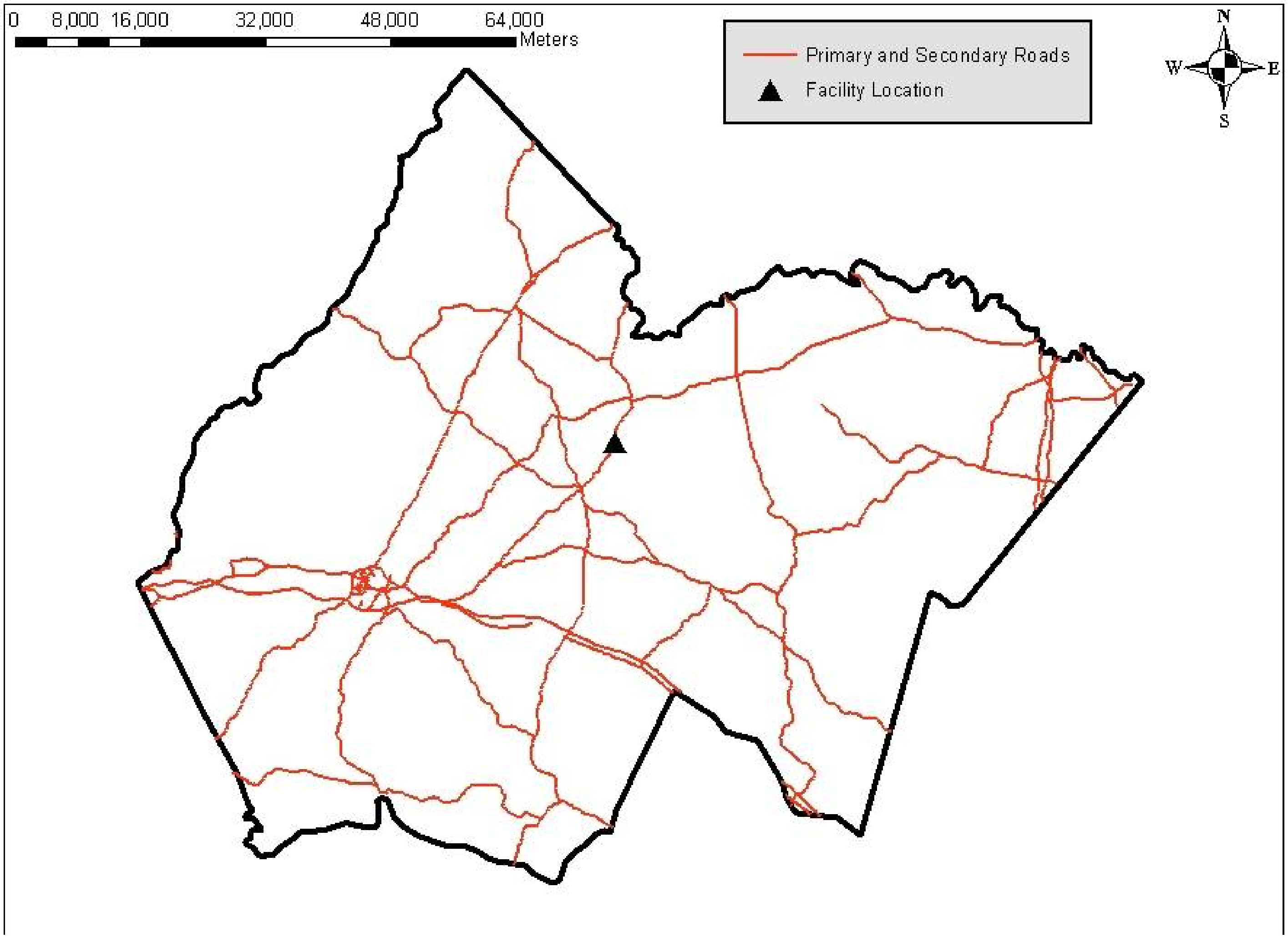


**Figure 5.11 Optimal facility location, NPV region**

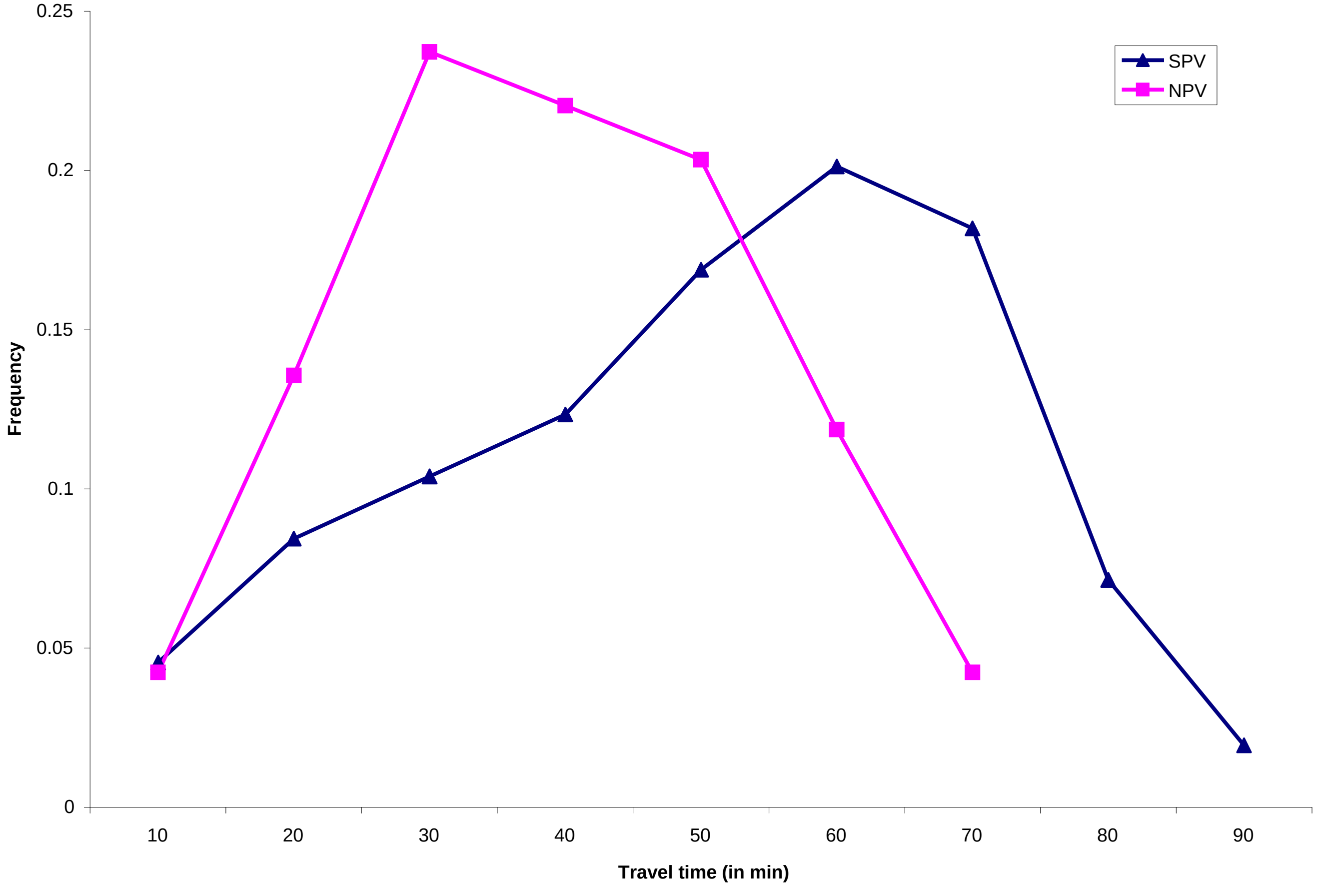


**Figure 5.12 SPV and NPV travel times**

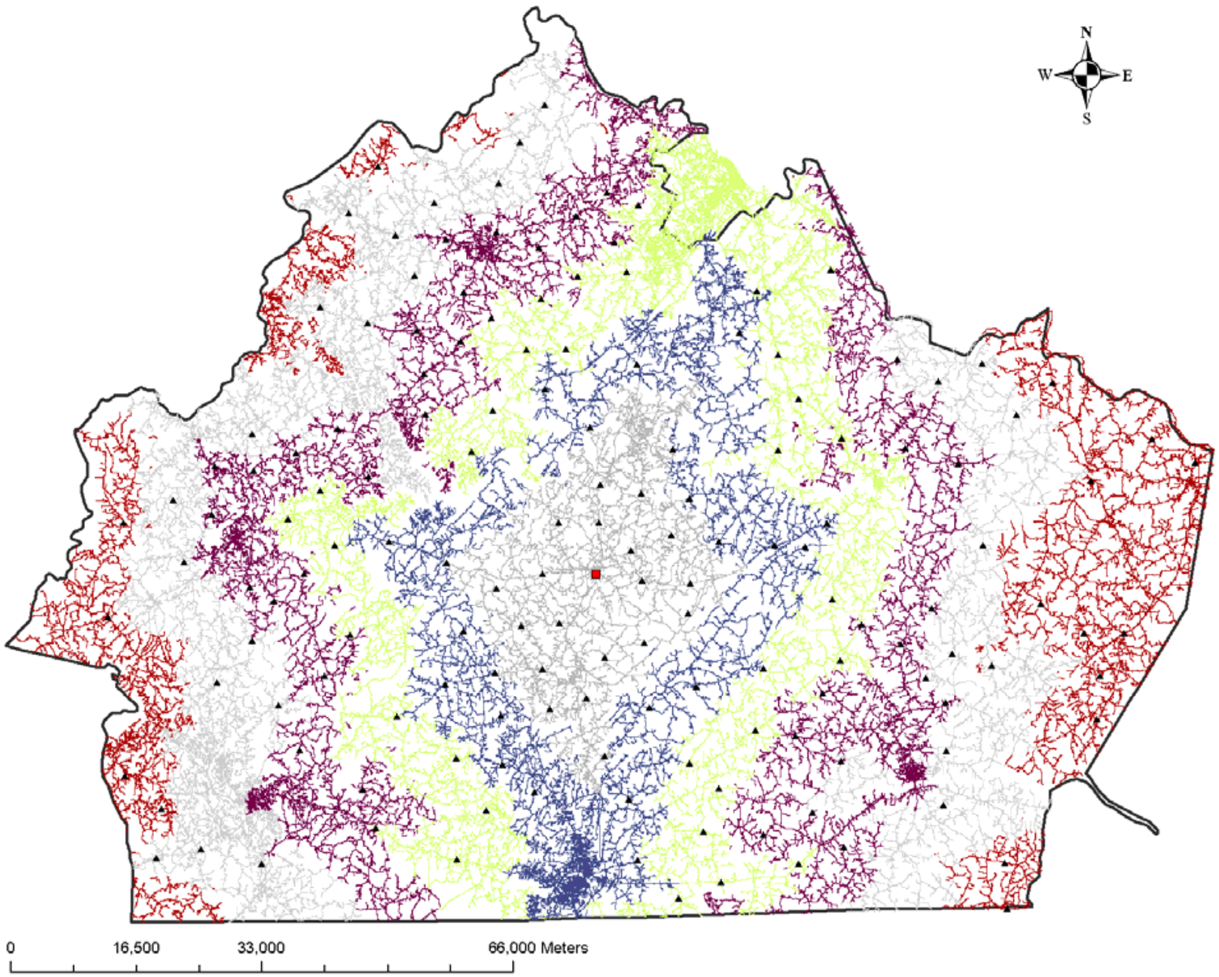


**Figure 5.13 SPV travel time contours**

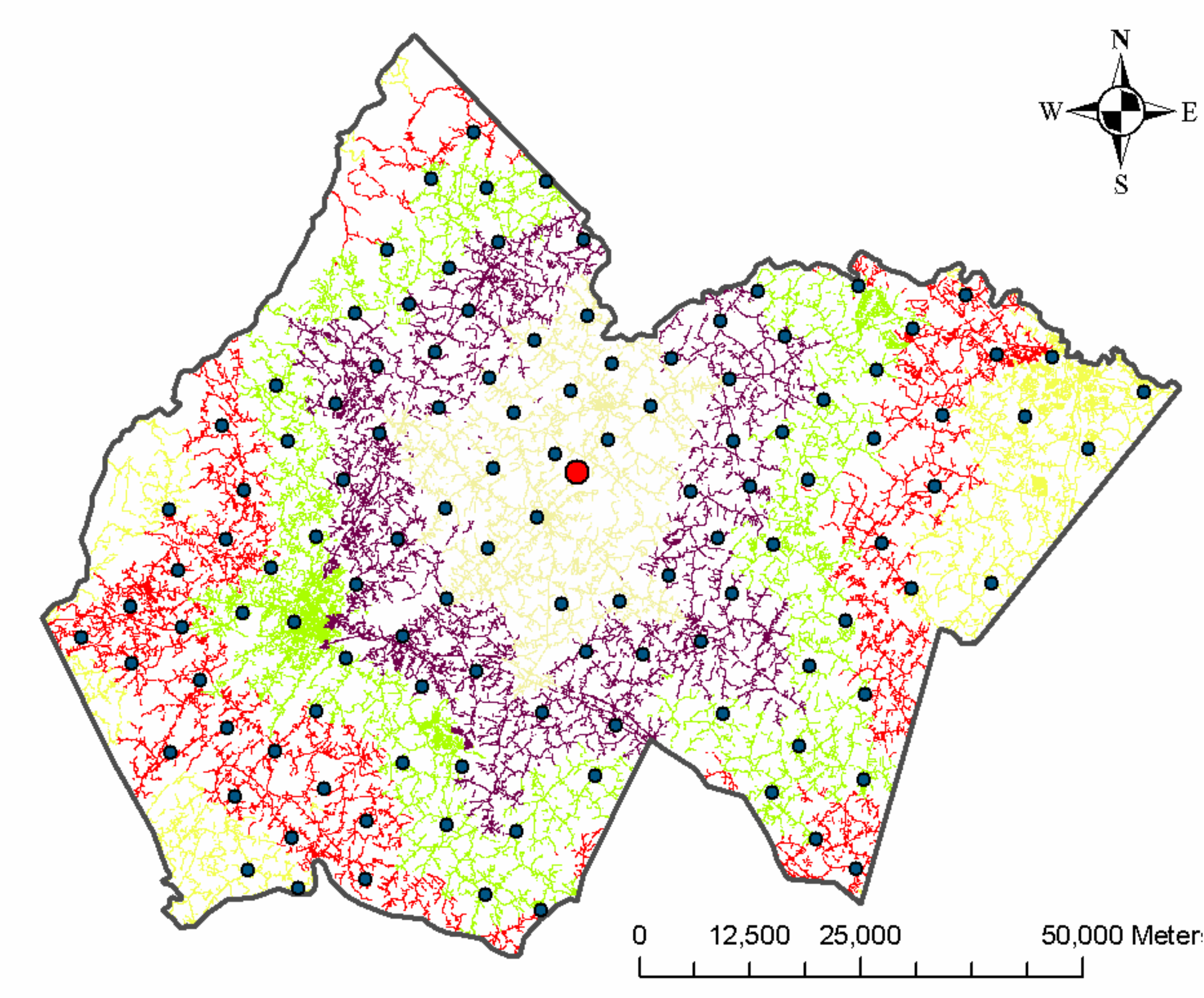


**Figure 5.14 NPV travel time contours**

# Chapter 6 – Strategies for Scheduling of Loaders and Trucks

## 6.1 Introduction:

### 6.1.1 Justification:

The cost of road travel in the logistic system to and from a biomass processing plant is determined by the location of the plant with respect to a given set of SSLs. It is therefore imperative that the plant location is chosen with utmost care and after extensive analysis. Chapter 5 examined this in detail.

The next step in this analysis is to operate a truck fleet from the plant to the SSL locations generated in Chapter 5. Due to the specialized nature of these trucks, any excess trucks not used for transporting loads on any given day cannot be reassigned for other productive purposes and the trucks will remain idle. The capital cost of owning these trucks will be reflected in the higher cost of biomass delivered to the plant.

So, the goal of any scheduling policy implemented by the plant has to reduce the maximum number of trucks needed during a season. This chapter examines seven different management policies to route the trucks and the effect of such policies on the maximum number of trucks needed by the system.

### 6.1.2 System Description:

In this system, the number of trucks needed by a given SSL will depend on the travel time from the plant to that SSL. The SSLs that are closer to the plant will need fewer numbers of trucks than a SSL that is at the outer boundary of the procurement region. Thus, the total number of trucks needed for this transportation system will vary as the

SSLs being serviced on any particular day changes. This variation in number of trucks will cause some trucks to idle during the season and operate at reduced productivity. The goal of this chapter is to reduce the variation while supplying the processing plant with required amount of material.

For example, assume all loaders are assigned to SSLs that are at the extreme edge of a plant's procurement region. Each of these SSLs will require a relatively larger number of trucks to operate the loader at the design capacity of 15 loads per workday than SSLs that are closer to the plant. As the season progresses, the loaders will move closer to the plant decreasing the travel time. With reduced travel times, each truck can move more number of loads per day and the total number of trucks needed by the system also decreases.

To illustrate this point further, refer to Figure 6.1. The figure shows a two loader system in operation. At the initial starting point, both loaders 1 and 2 need five trucks to transport 15 loads per day from their SSLs. At the closest point to the plant, each loader needs only 2 trucks, leaving six trucks idle. The type of loader assignment described in Figure 6.1, with decreasing truck travel time as season progresses, is referred to as Longest Travel Time first, or LTT, loaders.

As previously mentioned, the goal of this chapter is to determine a scheduling policy that will reduce this variation in truck requirement and keep idle trucks to a minimum while satisfying the demand for biomass from the plant. To achieve this goal, half of the loader's schedules were reversed such that their truck requirement goes up while the truck requirement of the other half goes down.

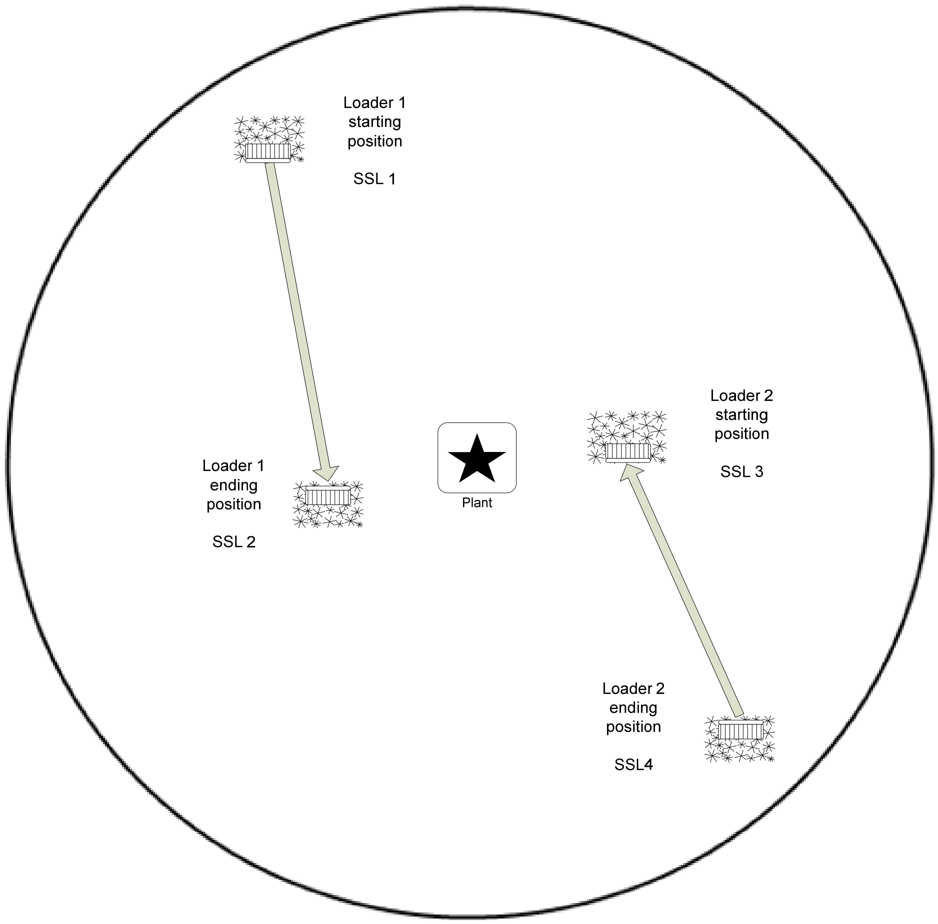


**Figure 6.1 Loaders 1 and 2 both following Longest Travel Time (LTT) policy**

For example, consider a variation of the scenario described in Figure 6.1. Loader 1 starts from the same position as before and starts working towards the plant, while Loader 2 starts from a SSL closer to the plant and works towards the outer boundary (Figure 6.2). In this scenario, the order of SSLs for Loader 2 is reversed from the previous example. At the beginning and at the end of the run, the system will be using seven trucks. This reduces the total truck requirement by 30% during the initial and final parts of the season.

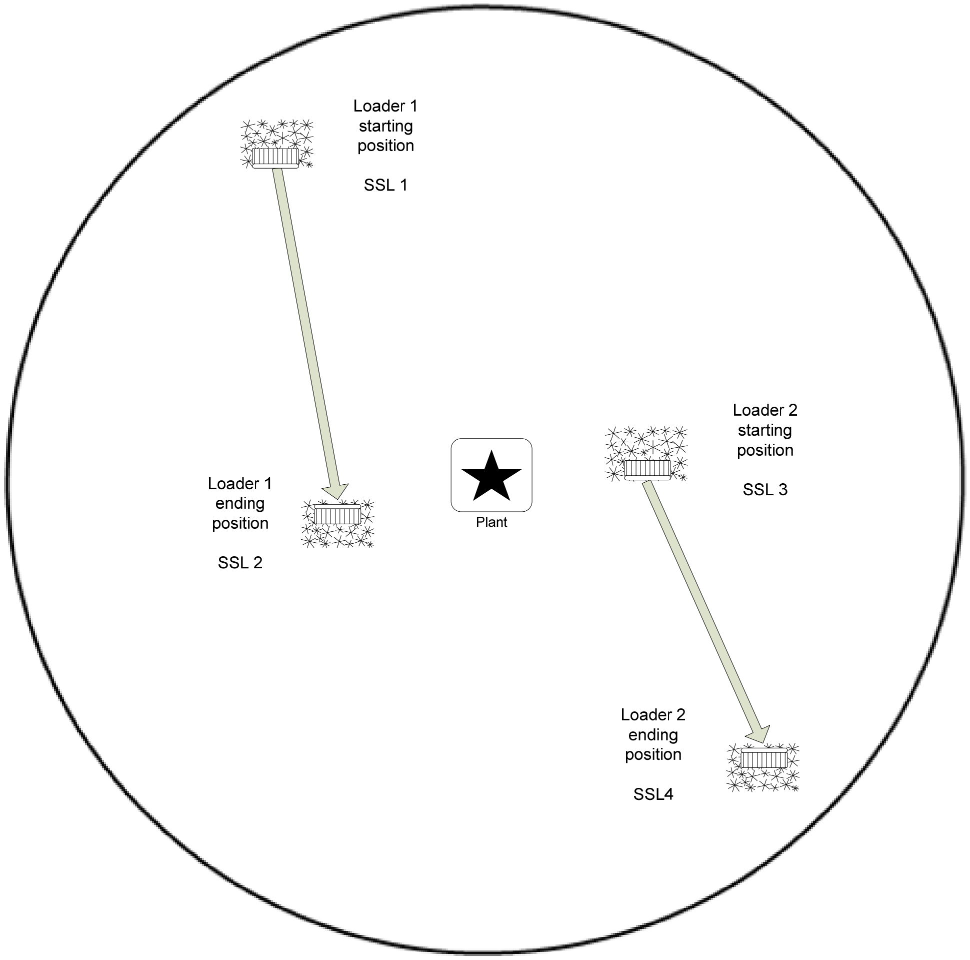


**Figure 6.2 Loader 1 with longest travel time (LTT) and Loader 2 with shortest travel time (STT) policy**

It is important to note that this technique may not reduce the number of idle trucks during the entire season to zero, because the system depends on the number of SSLs with 2, 3, 4 and 5 truck requirements in each loader's schedule. Suppose, Loader 2 exhausted all SSLs with a 2-truck requirement and moved on to SSLs with a 3-truck requirement before Loader 1 is done with all 5-truck SSLs. In this scenario, the total truck requirement of the system goes up from seven to eight as three trucks are needed to operate Loader 1 and five for Loader 2. Even with this additional truck, the maximum number of trucks that the plant needs to buy is less than previous scenario and the number of idle trucks is reduced from six to one. The loaders that follow a policy of increasing truck travel times are referred to as Shortest Travel Time first, or STT, loaders.

For this study, the proposed plant's demand was set at 50 Mg/h. With each truck load containing 14.4 Mg, the plant consumes 3.5 loads per hour. Since the plant operates 24/7, and the transport system operates only 12 hrs per day and 5 days per week, the system must transport (50)(24)(7)/[(14.4)(5)] = 117 loads per day. The loader in this study has an operational capacity of 15 loads per day, assuming no waiting time for trucks. With 8 loaders, the system can supply 120 loads per day when all 8 loaders are operational.

As the season progresses, each loader will move to the next SSL in its schedule list as soon as the current SSL is exhausted. If the current SSL is exhausted on Friday, the loader has Saturday to move and starts normal operations on the following Monday. But, if the SSL is exhausted on any other workday, the loader looses one workday to transport the load to the next SSL. It was expected that this constraint, along with the fact that the maximum capacity of the transportation system with 8 loaders being very close to 117 loads, will not let the transportation system supply the required number of loads to the plant. So, a decision to project outcomes with both 8 and 9 loaders was made.

Five different policies for scheduling the order of SSLs using the principles discussed in Figure 6.2 along with two sector based loader allocation were explored for the logistics system in SPV region. Each policy was simulated with 50%, 45% and 40% utilization of pasture land available in a given 3.2 km radius surrounding each SSL. This variation in utilization factor reflects the effect of decreasing land in biomass production and can also be used to gauge the effects of a drought or competing economic activity targeting the same procurement area.

Yields will be lower in a drought year, so each location will have less stored material, and the transport system has to procure material from additional SSLs located at a higher travel time from the plant. The average hauling cost per Mg may increase in this case, as these additional SSLs will require a larger truck fleet size.

## 6.2 Policy 1 – Shortest Travel Time first and Longest Travel Time next, with Contours (STT-LTT-C)

In Policy 1, Loaders 1 to 9 are assigned to SSLs in the following order. The SSL set is sorted in ascending order based on travel time from the plant to SSL locations. Loader 1 was filled first and starts from the SSL closest to the processing plant and works away from the plant towards the outer boundary of the supply area. In other words, the SSLs from the top of the list are assigned to Loader 1 till all 25 weeks of Loader 1 is full and cannot take in any more SSLs for that season. The SSLs that are assigned to Loader 1 are removed from the set. Once Loader 1's schedule is filled, SSLs are assigned to Loader 2 in the same order of travel times from the remaining set of SSLs. Loaders 3 and 4 are filled in similar fashion.

Loaders 5, 6, 7, 8 and 9 follow a similar method, but the SSLs are ordered with decreasing travel times in their schedule. That is, once Loader 4 is filled, Loader 9 starts filling with remaining SSLs but will order them in decreasing travel time within its schedule. The first SSL in Loader 9 will have a larger travel time than the last SSL, but all of Loader 8's SSLs will have larger travel times than Loader 9's maximum travel time. In this manner, Loader 7's SSLs will have larger travel times than Loader 8's maximum travel time, and Loader 6's SSLs will have larger travel times than Loader 7 and so on. An additional step is needed since not all SSLs are used under all three land use criteria and the SSLs with the highest travel times are discarded as the utilization percentage is inceased. Figure 6.3 shows the flowchart for this process.

Figure 6.4 shows the SSL locations for Loader 1 to Loader 6 under management Policy 1. Figure 6.5 shows the shortest travel time SSLs for Policy 1 pictorially. The designation "M1L1-50" means Management Policy 1 (M1), SSLs allocated to Loader 1 (L1) and 50 is percentage pasture land used. The SSLs closest to the plant are assigned to Loader 1. The next closest ones are assigned to Loader 2 and so on. It may be noted that since travel time is based on actual road speeds and not Euclidian distances, some SSLs are assigned to Loader 2 although they appear closer to the plant than some SSLs in the Loader 1 map.

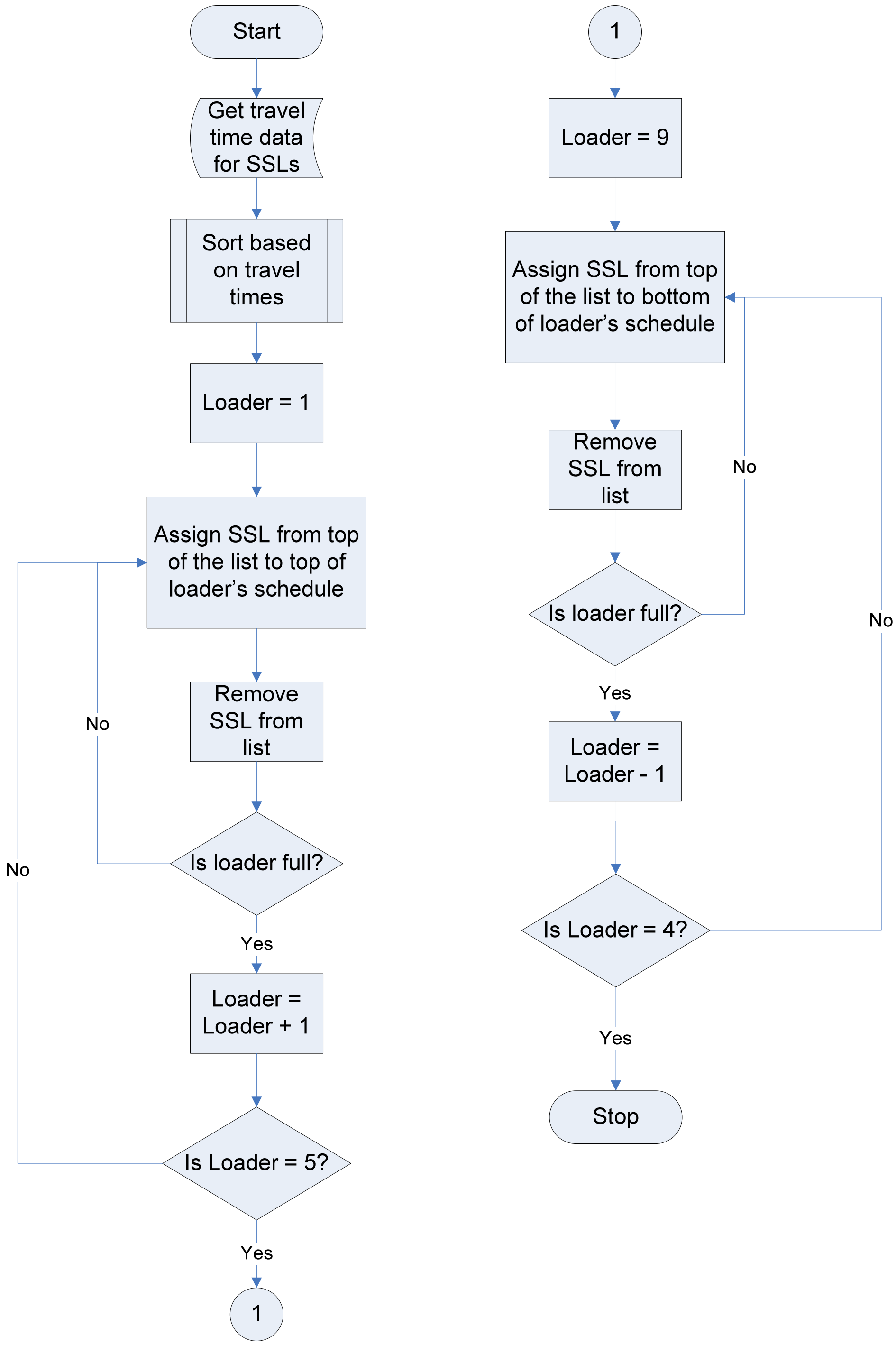


**Figure 6.3 Process flow chart for assigning SSLs to loaders under Policy 1**

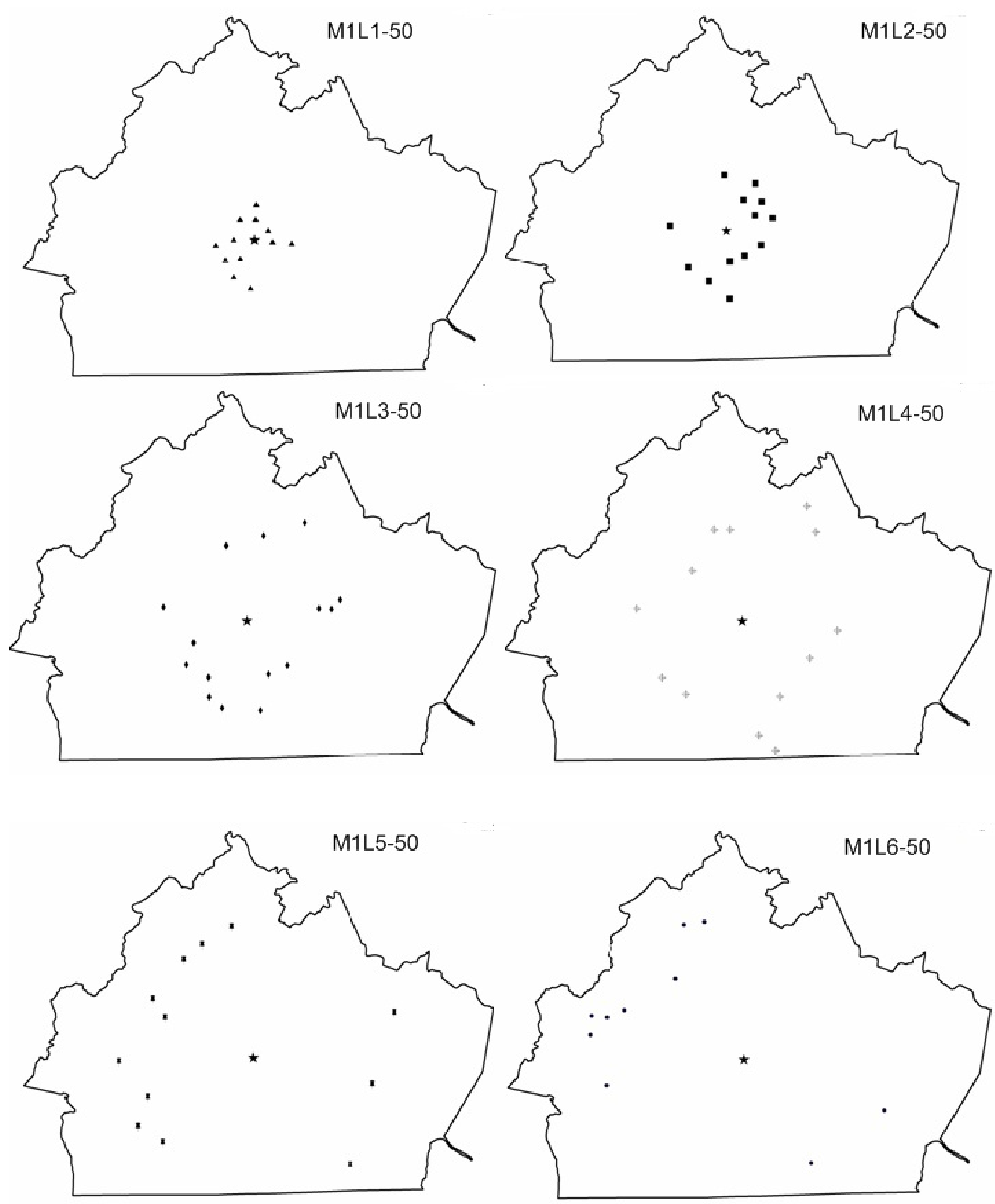


**Figure 6.4 SSL locations in management Policy 1, Loaders 1 to 6**

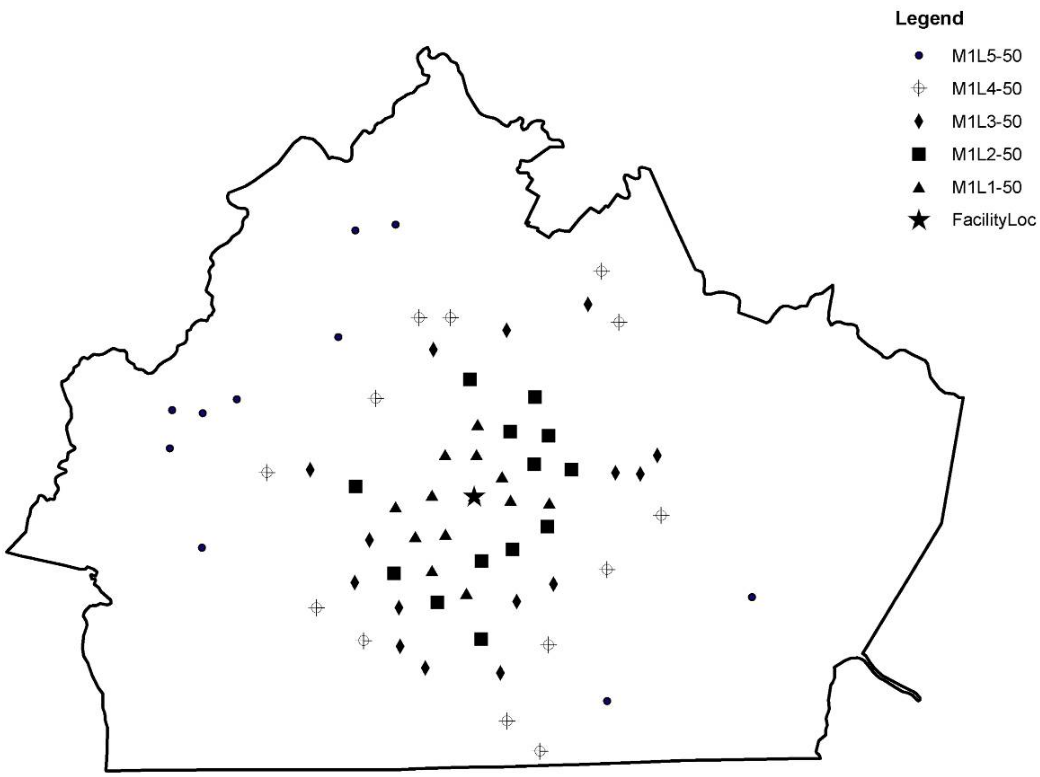


**Figure 6.5 STT SSLs (Loaders 1, 2, 3, 4) and LTT SSLs (Loader 5) in SPV region, Management Policy 1 (M1), 50% land use rate**

### *6.2.1 Policy 1 – Results and Analysis*

Figure 6.6 shows the truck utilization factor under Policy 1 along with number of trucks used by Loader 1. The truck utilization falls to zero when the loader has to move during the week. Figure 6.7 shows the same graph as Figure 6.6, but for Loader 2. The number of trucks used by Loader 2 increases from 2 to 3 during the course of its operation. This increase causes a decrease in truck utilization factor. This drop in utilization factor can be explained by the way the loader operates. Each loader can load a truck in 30 min and for this analysis, it is assumed that the load time is exactly 30 min. If Truck 1's loading starts at 0600 hrs, the load operation will complete at 0630 hrs and Truck 2's loading will start immediately afterwards. If Truck 1 returns to that particular SSL at 0645 hrs, the cycle time is 15 minutes. Loader 1 will be busy loading Truck 2 and Truck 1 will have to wait for 15 min. At 0700 hrs, loader will finish loading Truck 2 and can start loading Truck 1. This 15 min waiting time reduces the truck utilization factor as the truck is waiting in loader's queue.

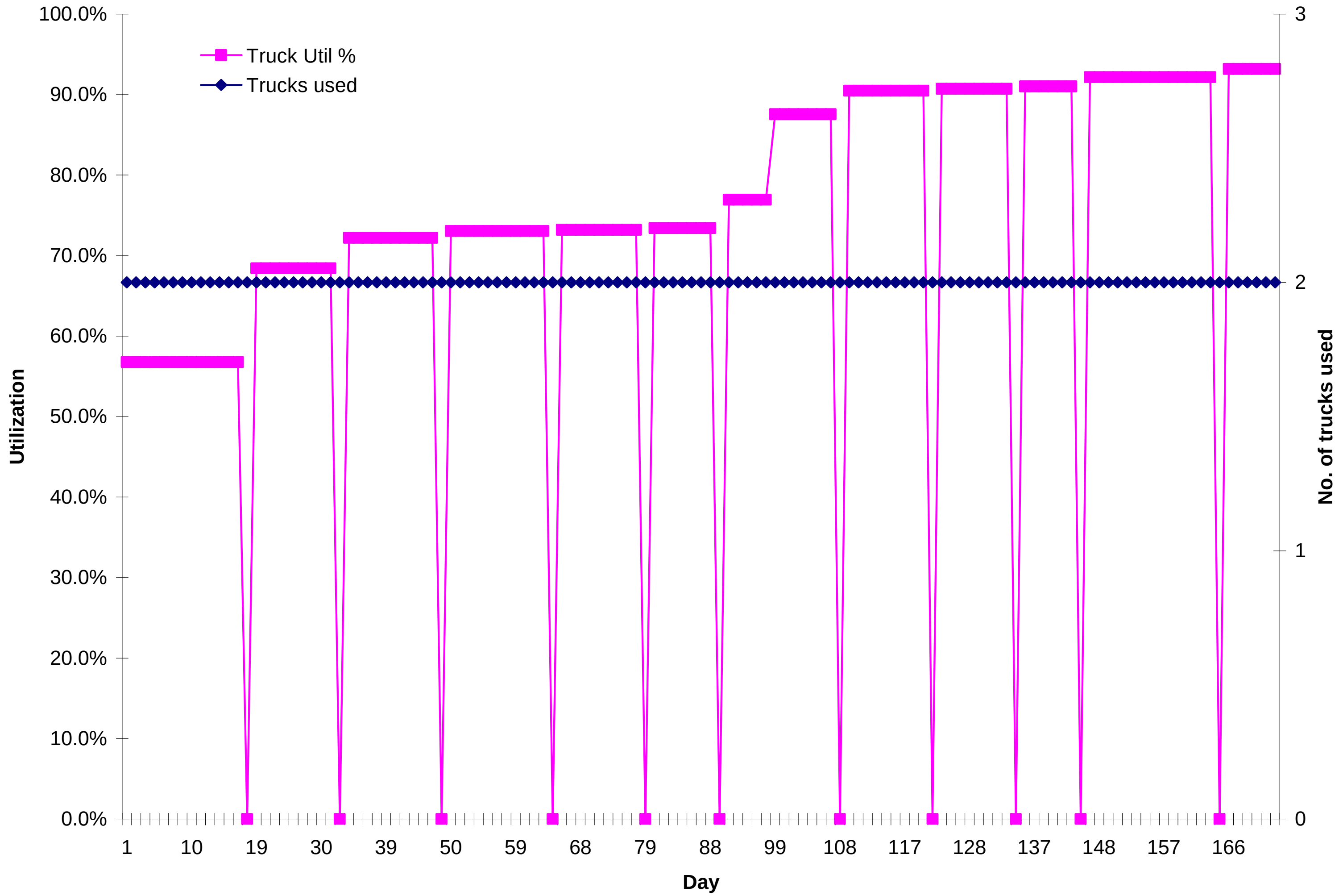


**Figure 6.6 Loader 1 truck utilization and number of trucks used in Policy 1, 50% land use rate**

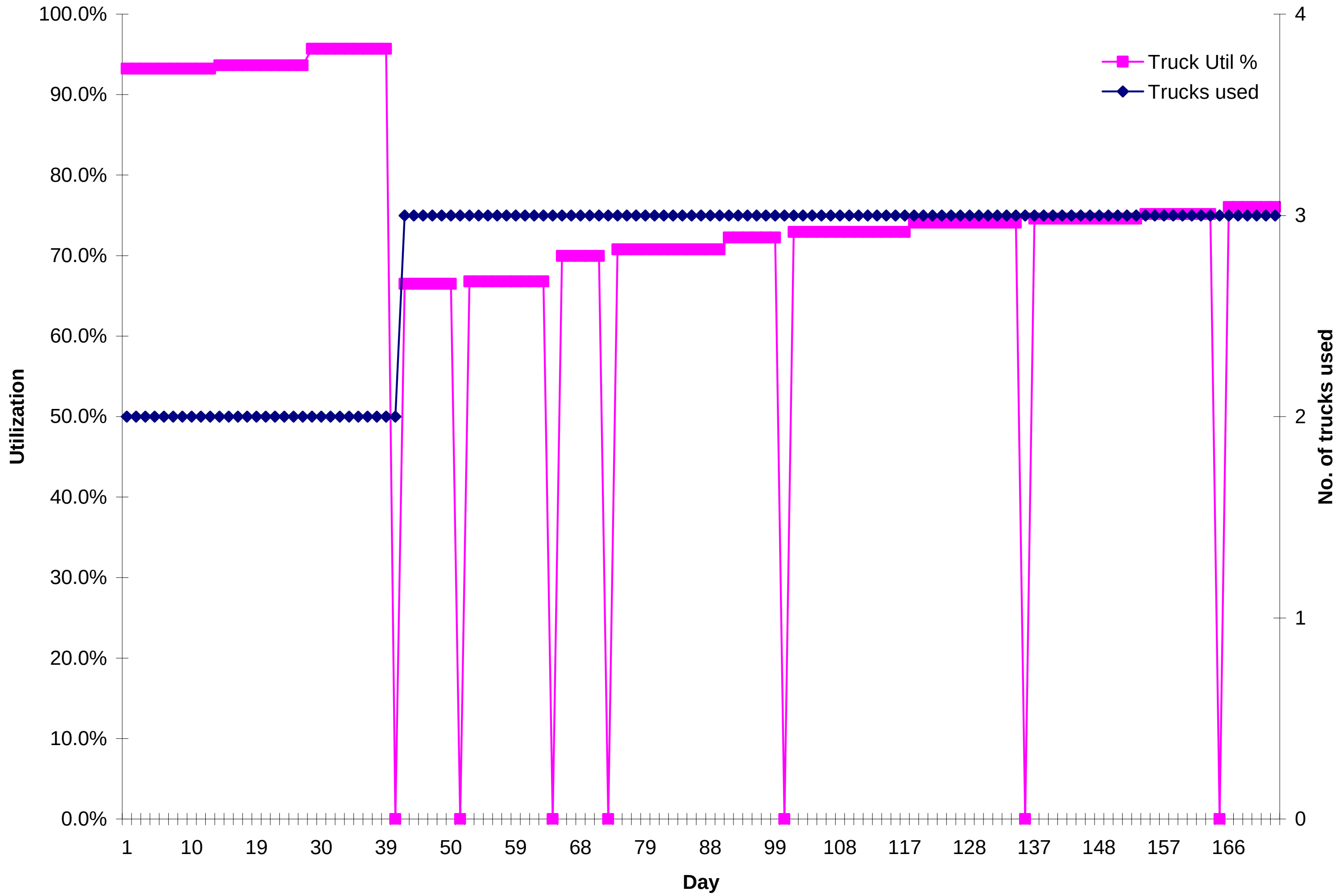


**Figure 6.7 Loader 2 truck utilization and number of trucks used in Policy 1, 50% land use rate**

Now consider a SSL that still uses 2 trucks, but is a little further away from the plant. Suppose the travel time from that SSL is 20 min. In this case, the truck only needs to wait for 10 min before its loading operation starts. This decrease in waiting time increases the utilization factor of the truck. When an SSL with 3 truck requirement is reached, this 30 min block will reset. That is, the waiting time can be any where from 29 min to 1 min. Due to the STT arrangement in this policy, the waiting time decreases and keeps on decreasing, all the while pushing up the utilization rates until there is a change in the number of trucks used. The increase in utilization factor gets flipped when loaders with LTTs are considered, as the order is in the opposite direction. Figure 6.8 shows this phenomenon for Loader 6. In this case, the truck utilization decreases as the loader moves to SSLs closer to the plant.

Figure 6.9 shows the total number of trucks used by management Policy 1 under all three land use rates. The variation in the number of trucks used is very small, between + or - 1 from median until the tail end of the run. This tail end is less than 5 days and is not considered a significant issue. With 34 trucks, Policy 1 can comfortably operate and cope with seasonal changes in yield without a large penalty cost as the maximum number of idle trucks will be 4, which is around 11% of total trucks.

Figure 6.10 shows the average truck utilization rate for all trucks under Policy 1 at 50% land use rate. The overall average truck utilization factors were 81%, 80% and 79% for 50%, 45 % and 40% land use rates, respectively.

Figure 6.11 shows the inventory level increase at the plant as the season progresses when using 8 loaders under Policy 1. Figure 6.12 shows the inventory level at the plant when using only 9 loaders. The inventory level at the plant steadily increases when operating 9 loaders and reaches a maximum of 1,236 loads (50% land use rate). This high level of inventory is expected to cause serious problems as the infrastructure to store this many loads at the plant is expensive.

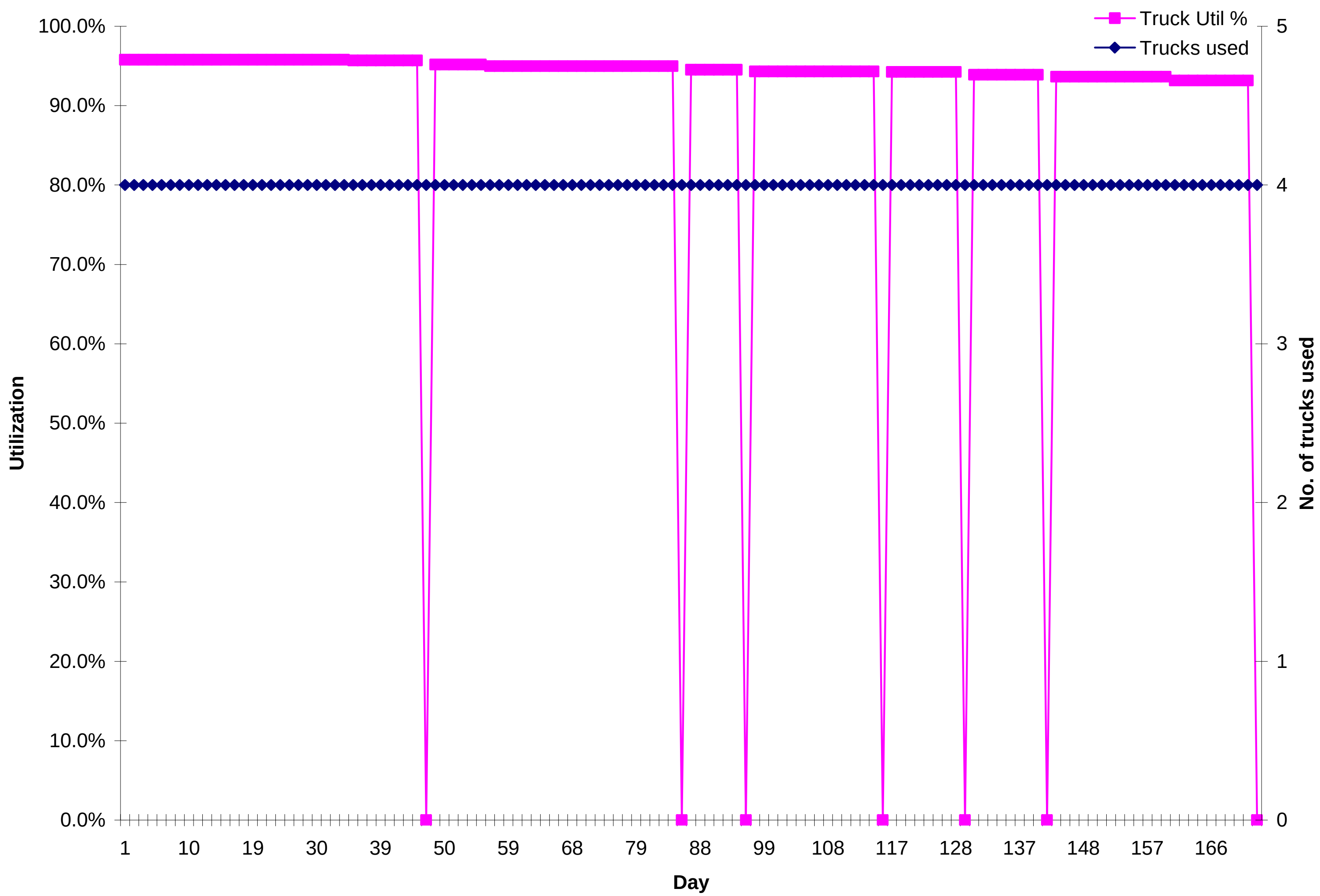


**Figure 6.8 Loader 6 truck utilization and number of trucks used in Policy 1, 50% land use rate**

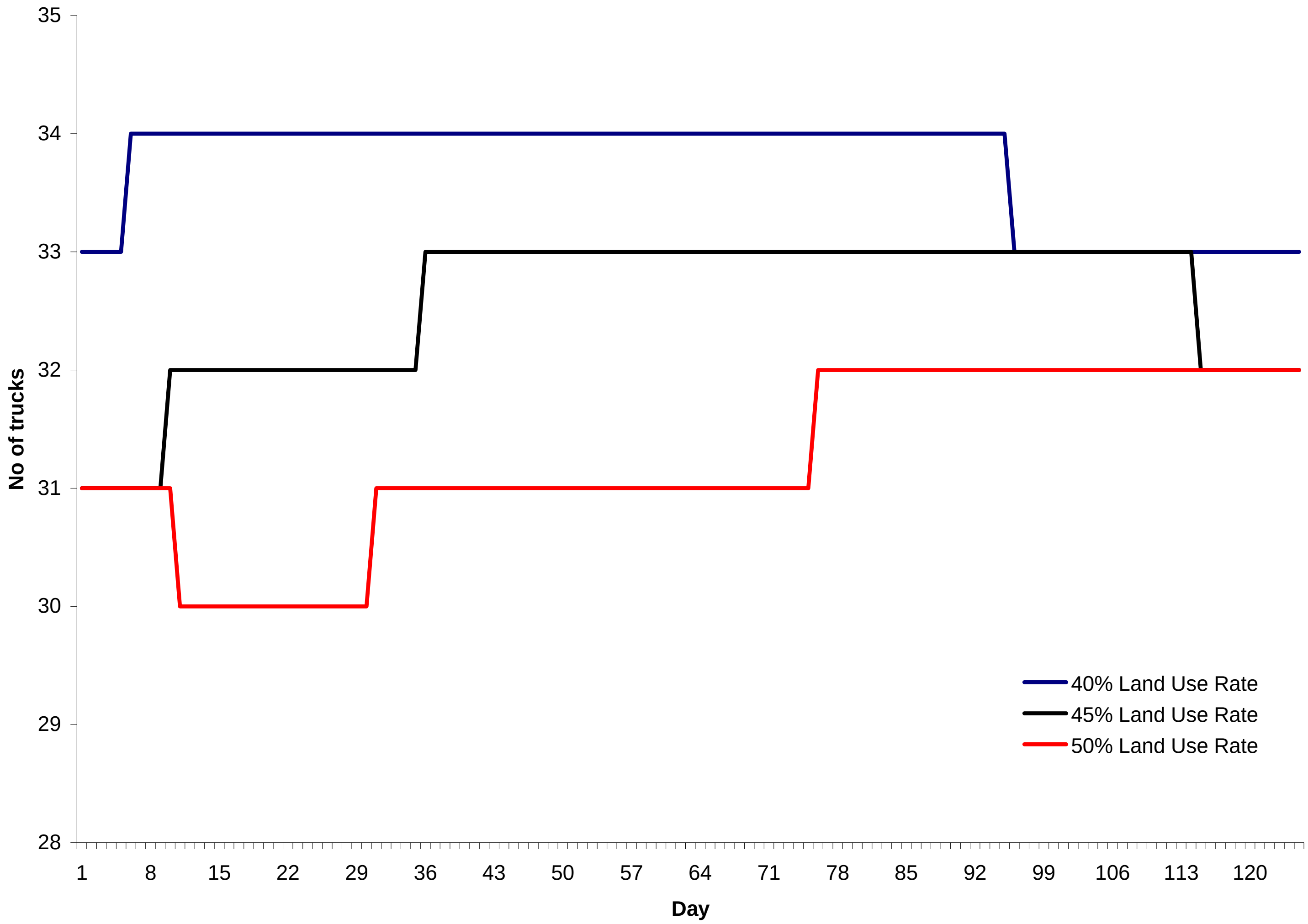


**Figure 6.9 Number of trucks used in Policy 1, by land use rates**

But when operating only 8 loaders, the logistics system is incapable of supplying the requisite number of loads. Even with an assumption of a very high initial inventory level of 1,000 loads at the beginning of the 6-month season, the system runs out of loads before the season ends. One way to address this issue is to operate the ninth loader at half its maximum operational capability. Loader 9 was selected for part-time operation as it has the SSLs with highest travel times.

Policy 1 assigns loaders to SSLs based purely on SSL-to-plant travel times. In the SPV production region, two SSLs that have similar (less than 1 min) travel time variation can be on the opposite sides of the plant. This causes some loaders to move from one end of the production region to another and back again as the season progresses. This overlapping of loader paths is referred to as “crisscrossing.”

As mentioned in section 6.1, this inter-SSL travel by loaders is low when compared to overall travel distances involved in this system, but contributes a significant cost to total logistics cost as loader travel has a higher cost. Figure 6.13 shows the inter-SSL travel of Loader 3 under Policy 1 along with some significant crisscrossing. Policies 4 and 5 address this issue and incorporate methods to reduce total loader travel.

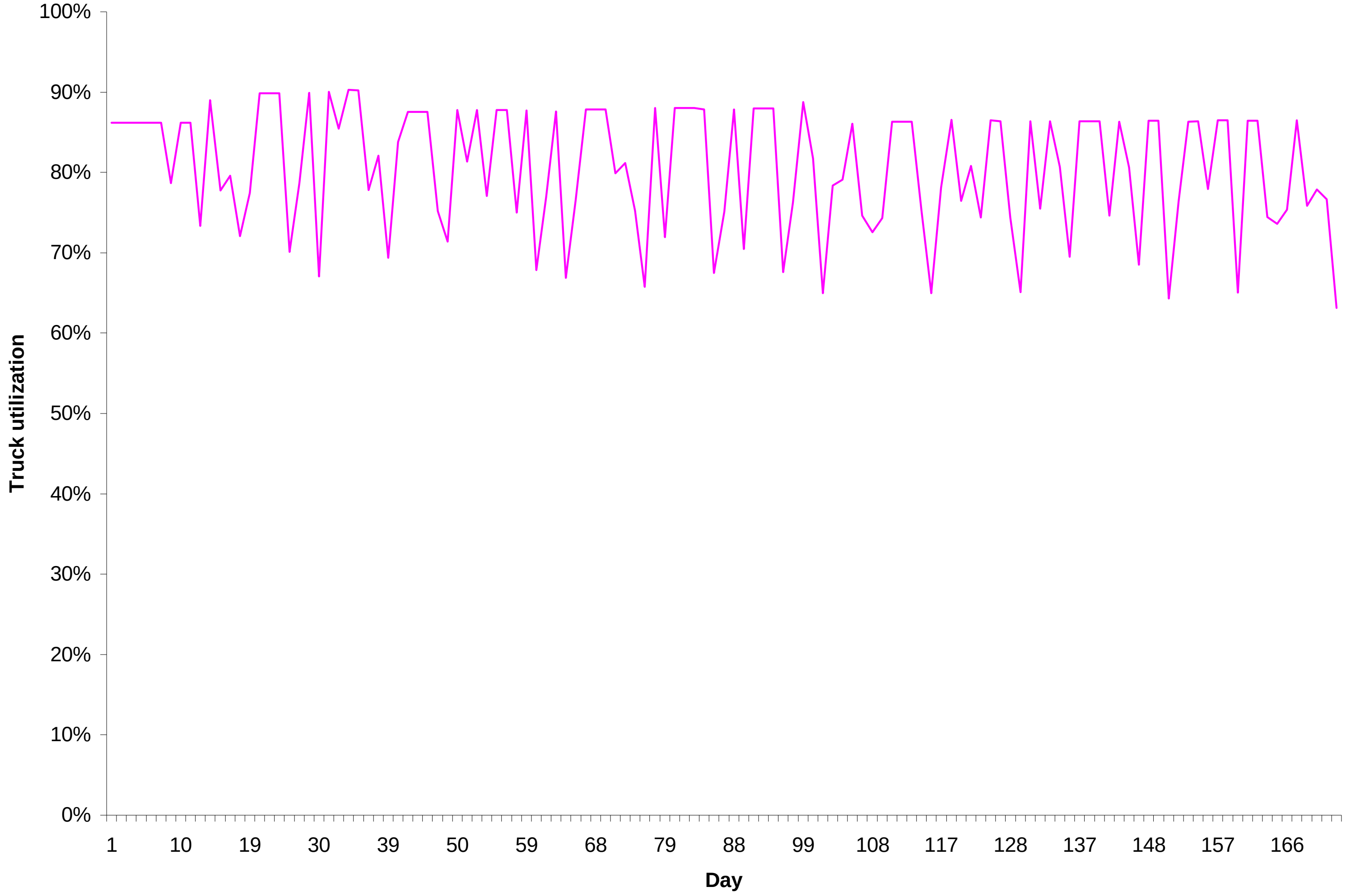


**Figure 6.10 Overall average truck rates in Policy 1 at 50% land use rate**

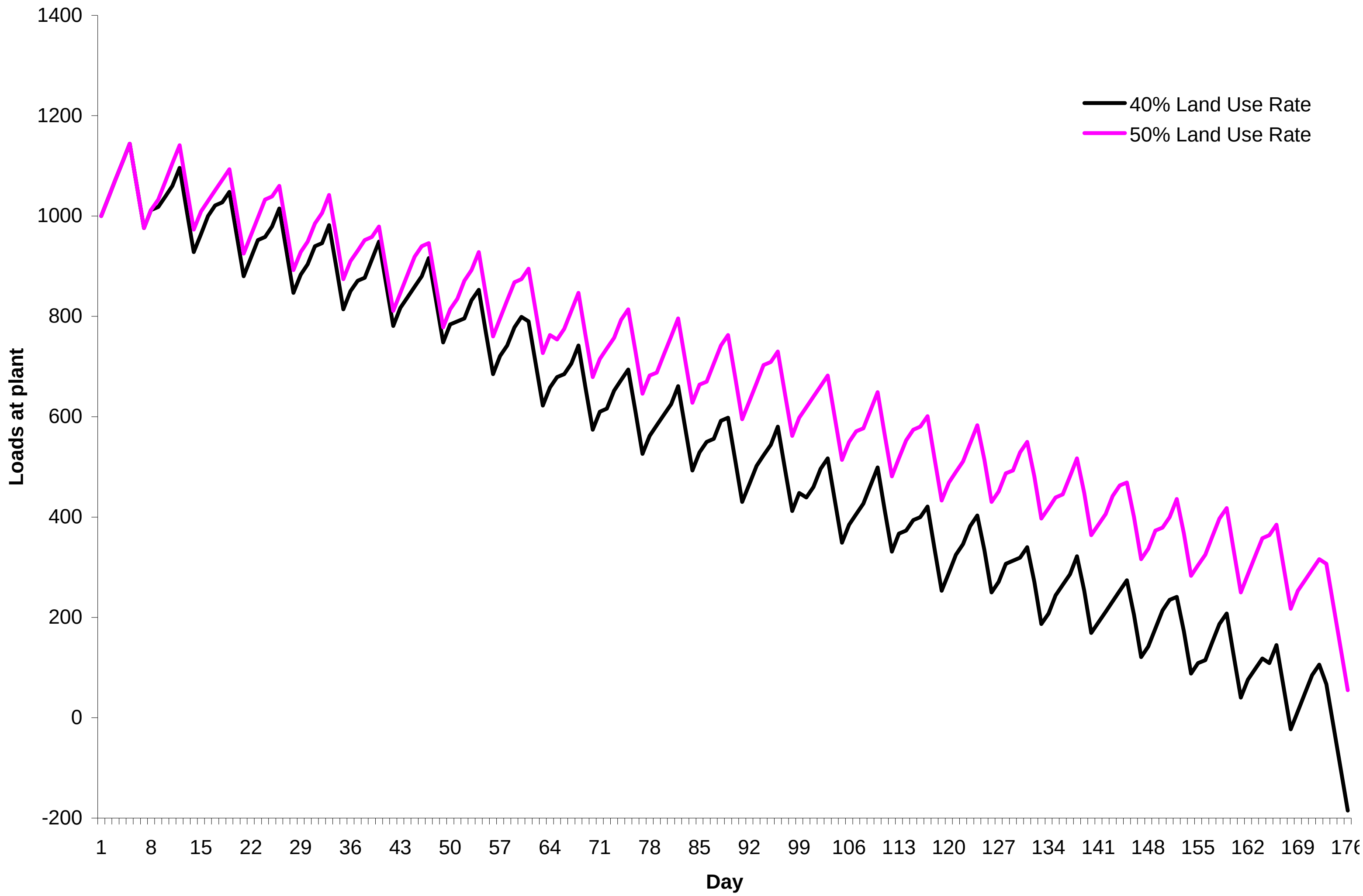


**Figure 6.11 Inventory level at the plant with 8 loaders, Policy 1, 40% and 50% land use rate**

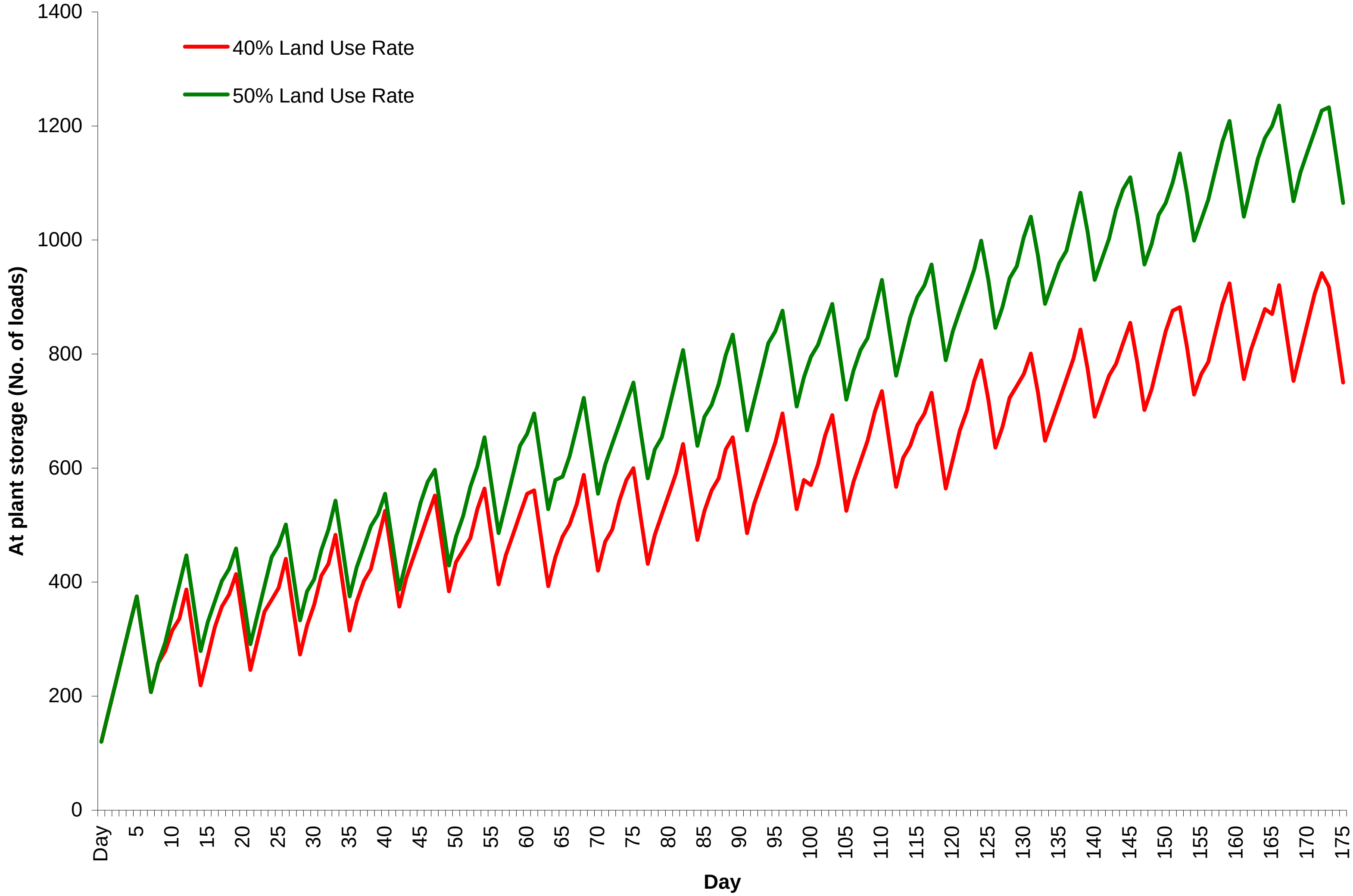


**Figure 6.12 Inventory level at the plant with 9 loaders, Policy 1, 40% and 50% land use rate**

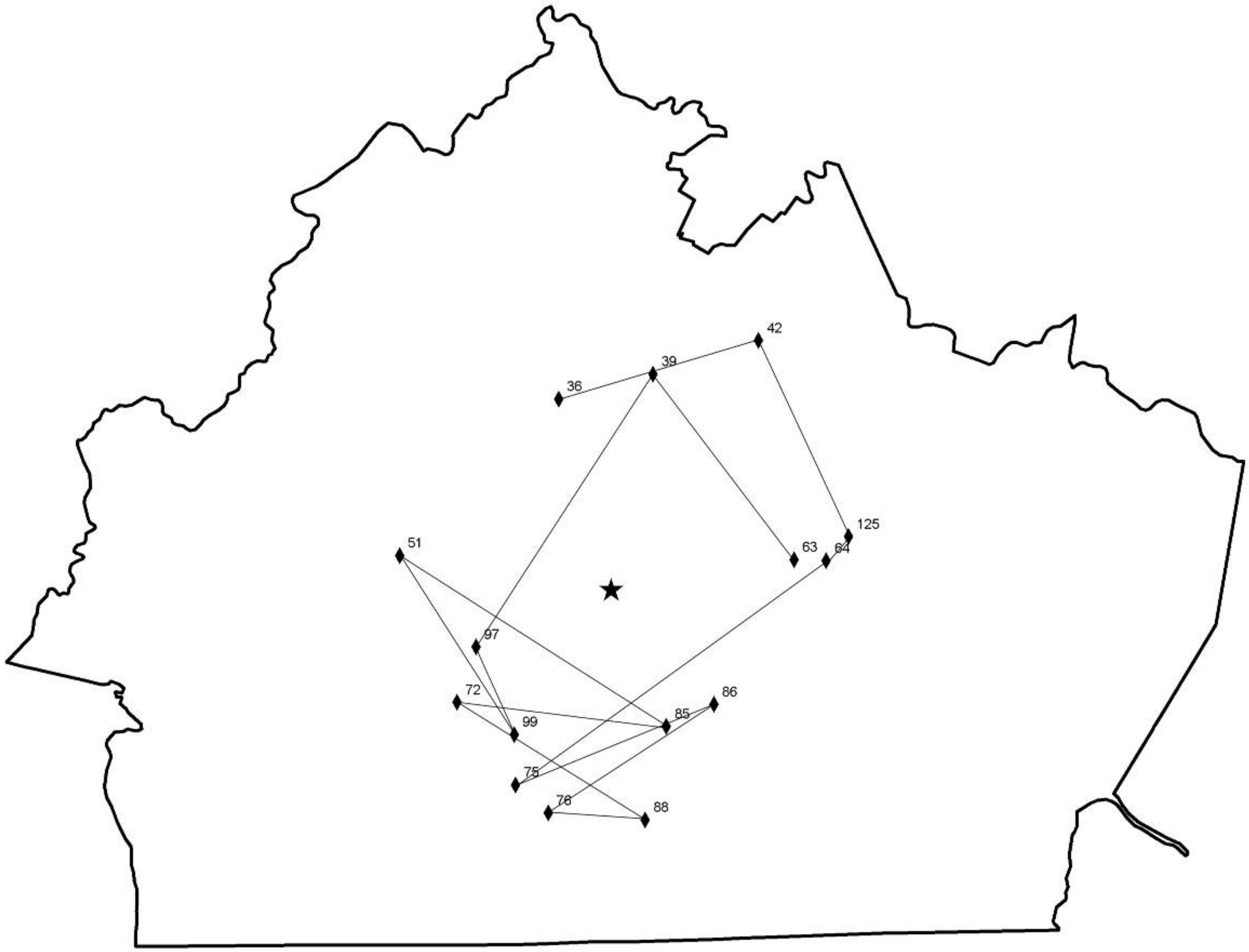


Figure 6.13 Inter-SSL travel of Loader 3 under Policy 1, 50% land use rate (SSL sequence is 36, 42, 125, 64, 75, 76, 76, 88, 72, 85, 51, 99, 97, 39 and 63)

## 6.3 Policy 2 – Shortest Travel Time first and Longest Travel Time next, without Contours (STT-LTT-WC)

In Policy 2, the SSLs are split into nine sections. Loaders 1 to 5 have all SSLs in STT order and Loaders 5 to 9 have SSLs in LTT order. In Policy 1, all SSLs assigned to Loader 1 had travel times less than the SSL with minimum travel time in Loader 2 and so on. In this policy, Loader 1 will have the SSL with shortest travel time, Loader 2 will get the SSL with second lowest travel time, and Loader 3 will get the third lowest travel time SSL and so on till Loader 5.

This process then repeats itself from Loader 1 until Loaders 1 to 5 are filled. The same mechanism is used to fill Loaders 6 to 9, but in LTT order. This policy forces all STT loaders to start close to the plant and move out, while LTT loaders start at the outer edge of the procurement region and move to the plant. Figure 6.14 shows the process flow chart for determining STT loader schedule and Figure 6.15 shows the process flow chart for LTT loader schedule. The resulting sequence for loaders 1 to 5 (STT loaders) is shown in Figure 6.16.

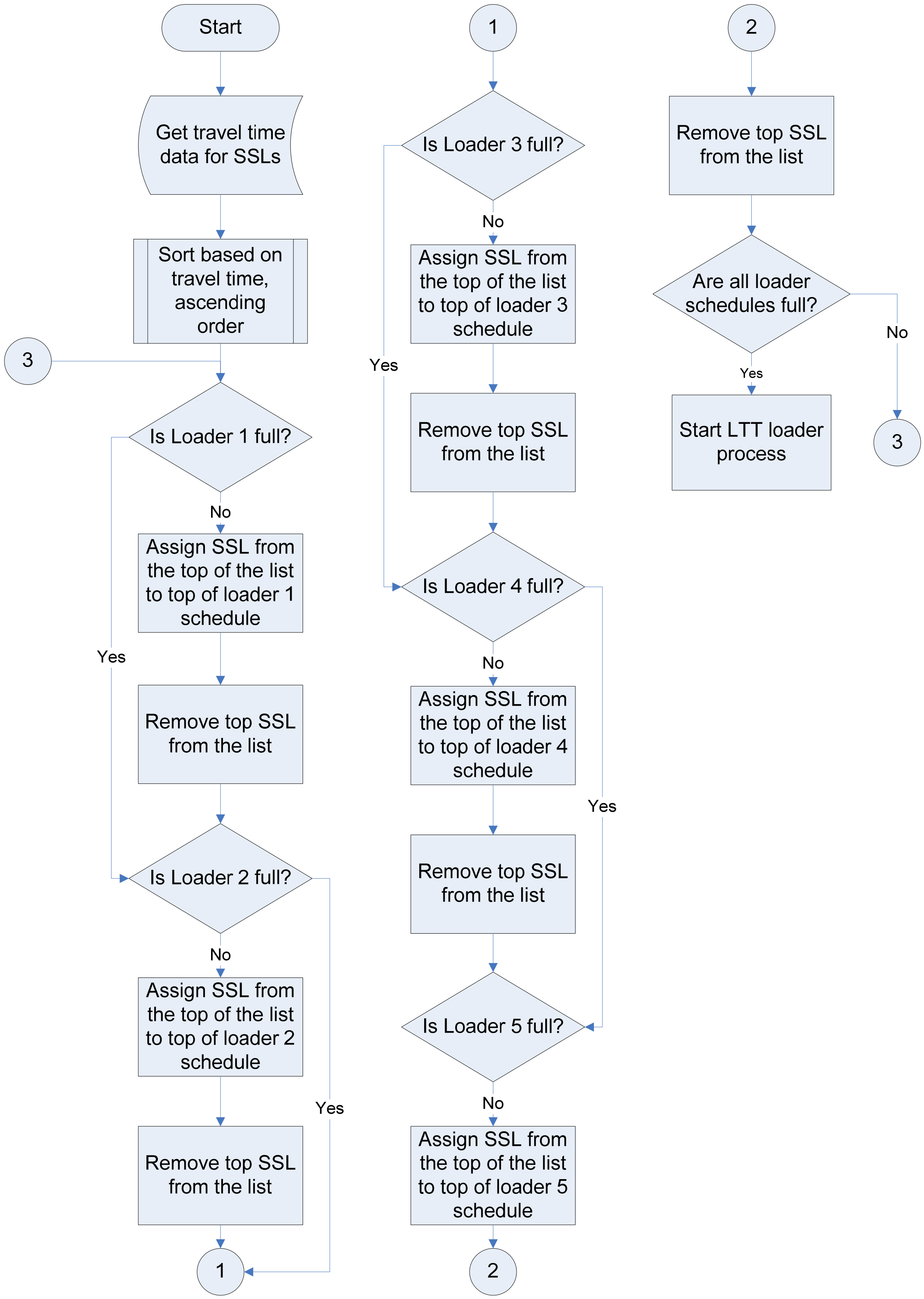


**Figure 6.14 Process flow chart for assigning SSLs to STT loaders (Loader 1 to 5) under Policy 2**

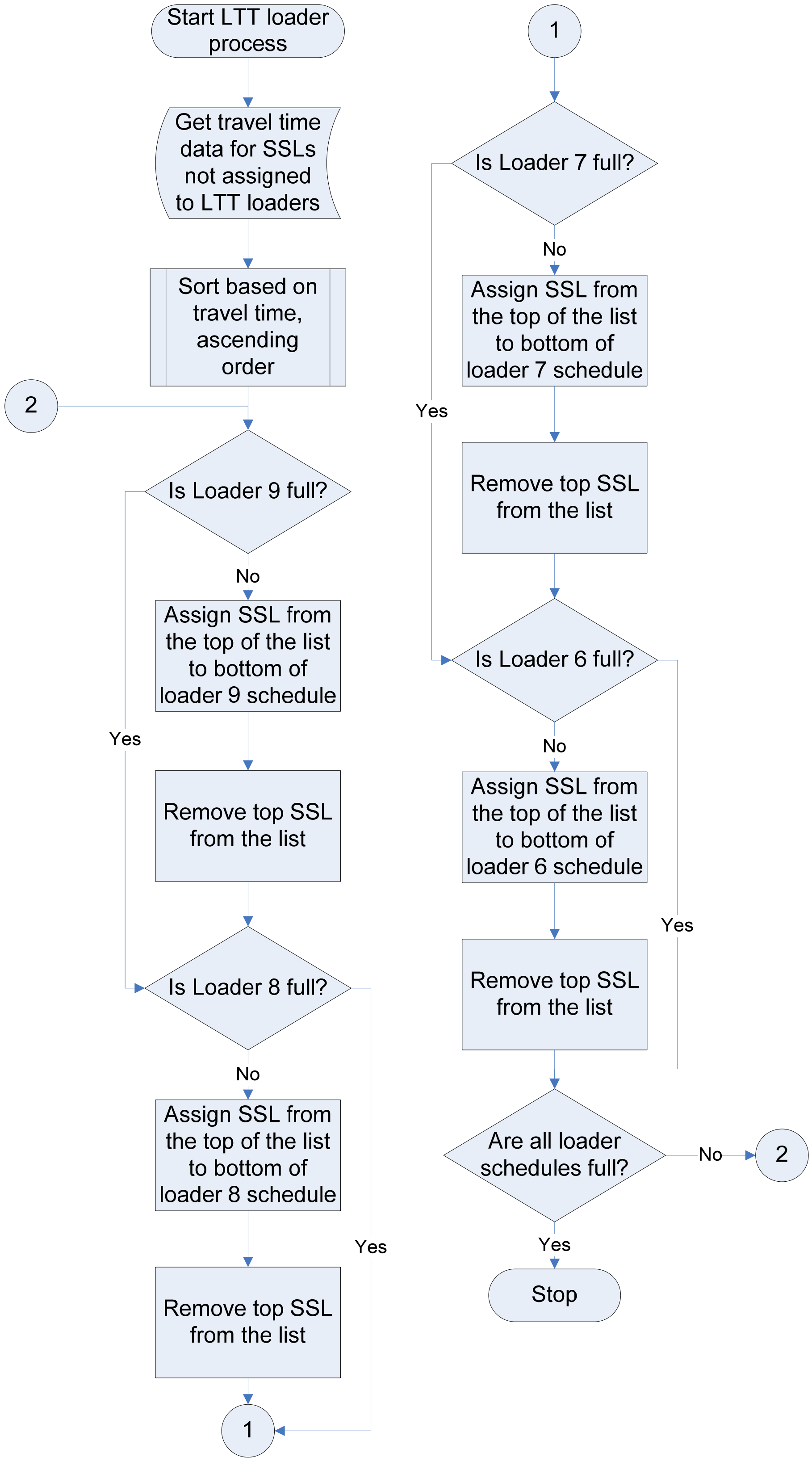


**Figure 6.15 Process flow chart for assigning SSLs to LTT loaders (loader 6 to 9) under Policy 2**

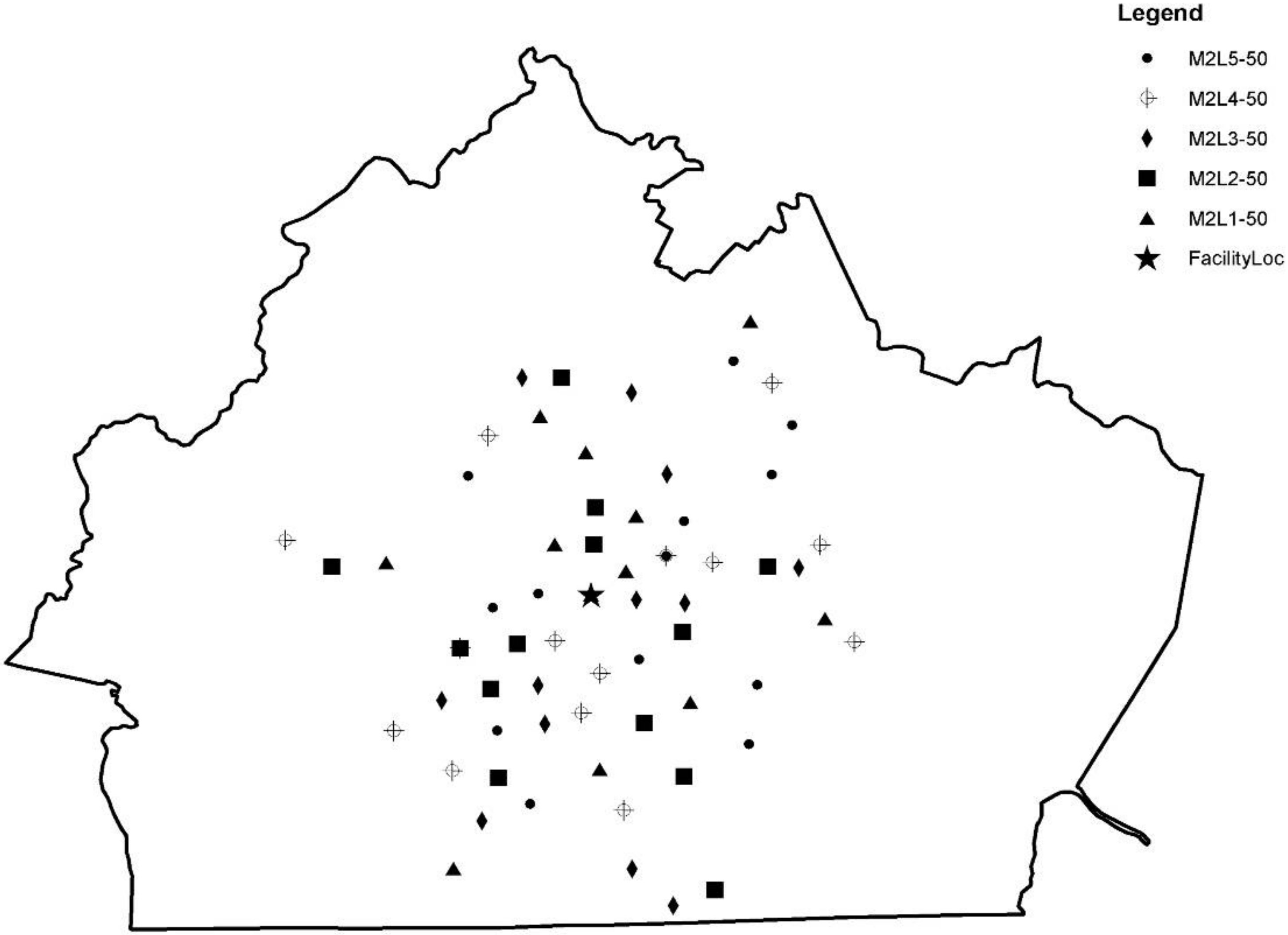


**Figure 6.16 SSLs assigned to Loaders 1, 2, 3, 4 and 5 in SPV (STT) , management Policy 2 (M2)**

### *6.3.1 Policy 2 – results and analysis:*

Policy 2 was analyzed for 50%, 45% and 40% land use rates. Figure 6.17 shows truck utilization rate and the number of trucks used by Loader 1 at 50% land use rate. Although similar to Figure 6.6, due to the differences in how the SSLs are split, the loader changes from SSLs requiring 2 trucks to 3 and then to 4. This did not happen with Policy 1. The variation in truck utilization rates as the number of trucks increases is more pronounced with Policy 2.

Figure 6.18 compares the inventory level at the plant when following Policy 2 and Policy 1. The at-plant inventory increases continuously and reaches about 1,100 loads at six months. An inventory this large represents a substantial cost to the plant. As the figure shows, Policy 2 lags behind Policy 1 by only a small amount. Figure 6.19 shows the total number of trucks used by Policy 2.

Surprisingly, the variation is between 25 and 35 trucks, which requires more trucks than Policy 1. This is due to the fact that there were a smaller number of SSLs with two truck requirement than four and five truck requirement. Therefore, as STT loaders were moving on to SSLs with 3 or more trucks, there was no corresponding drop in LTT truck demand. This mismatch caused a higher variation in total truck demand.

Figure 6.20 shows the overall average truck utilization rate for Policy 2 when operating under 50% land use rate. The average truck utilization was 81%, 80% and 79% for 50%, 45% and 40% land use rates respectively, which is comparable to Policy 1. The variation in total truck demand from 26 to 36 trucks is a significant disadvantage of Policy 2 since trucks are idled for a larger amount of time and will increase the average hauling cost. The increase in minimum number of trucks corresponding to the decrease in land use rate was caused by the addition of SSLs to satisfy demand. These additional SSLs have a higher truck requirement and they caused a spike in the initial truck demand. Due to the way Policy 2 is ordered, these SSLs were emptied first and as the season progressed, the truck requirement stabilized.

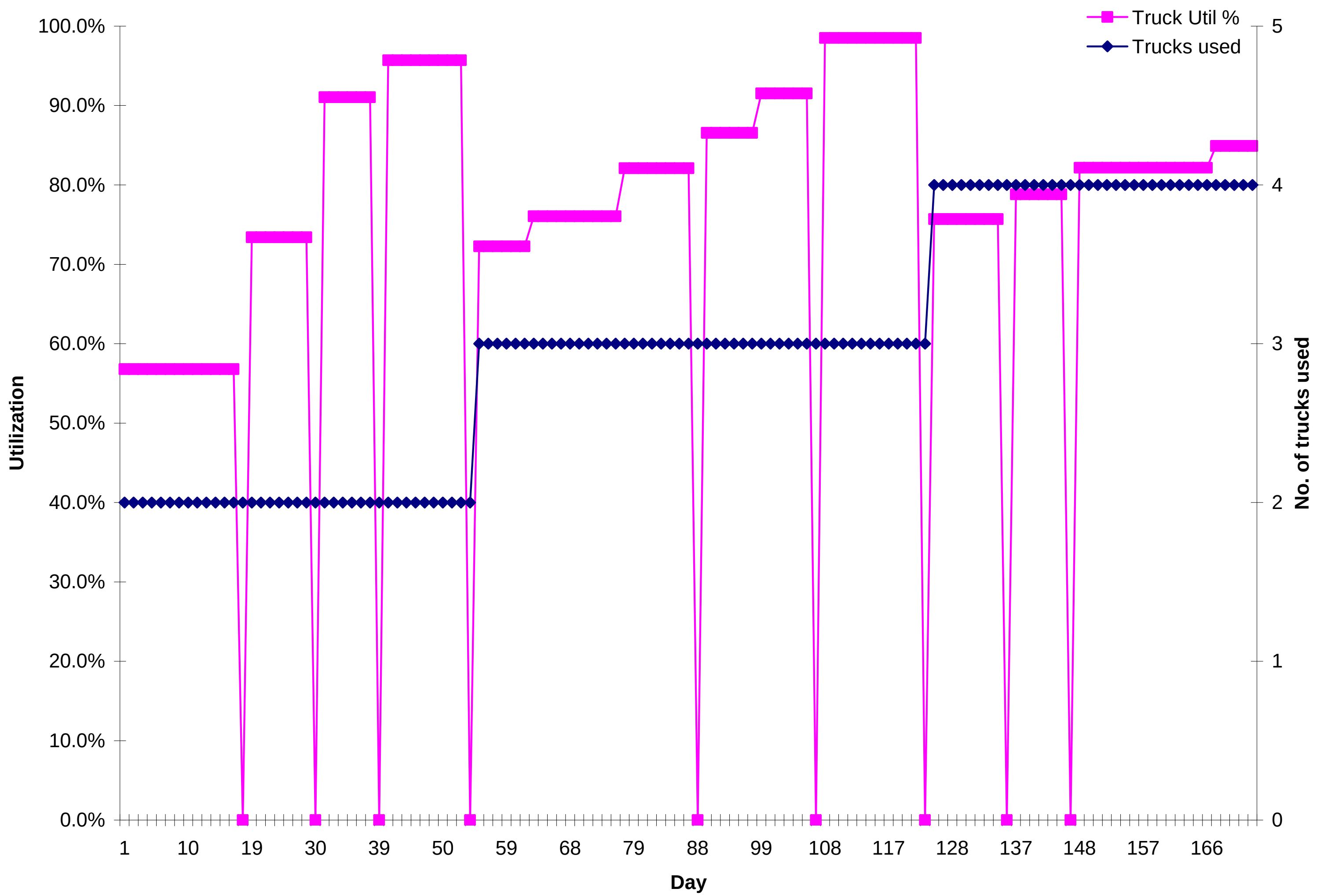


**Figure 6.17 Loader 1 truck utilization and number of trucks used in Policy 2,  50% land use rate**

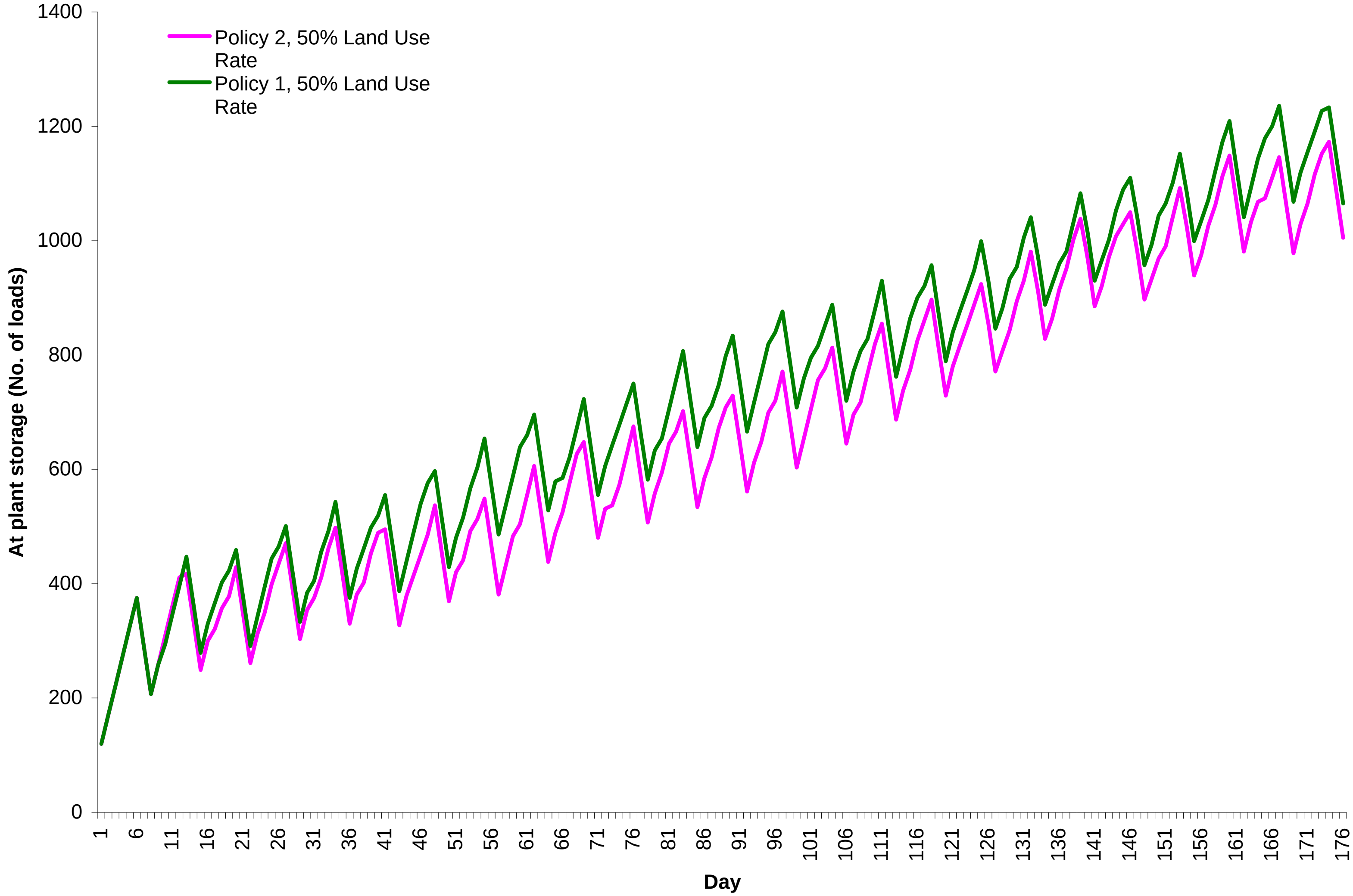


**Figure 6.18 Inventory level with 9 loaders, Policy 1 and Policy 2, 50% land use rate**

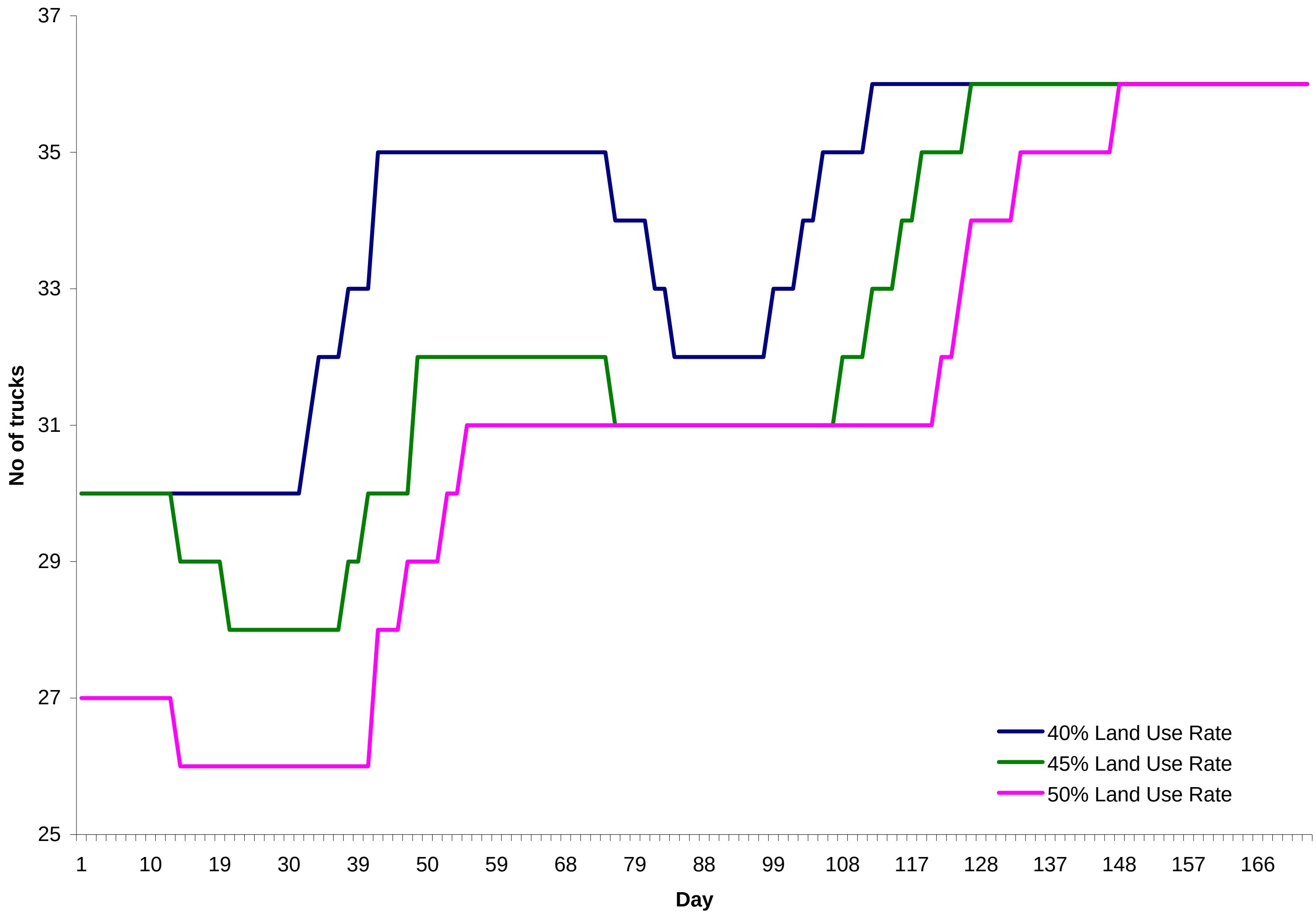


**Figure 6.19 Number of trucks used in Policy 2**

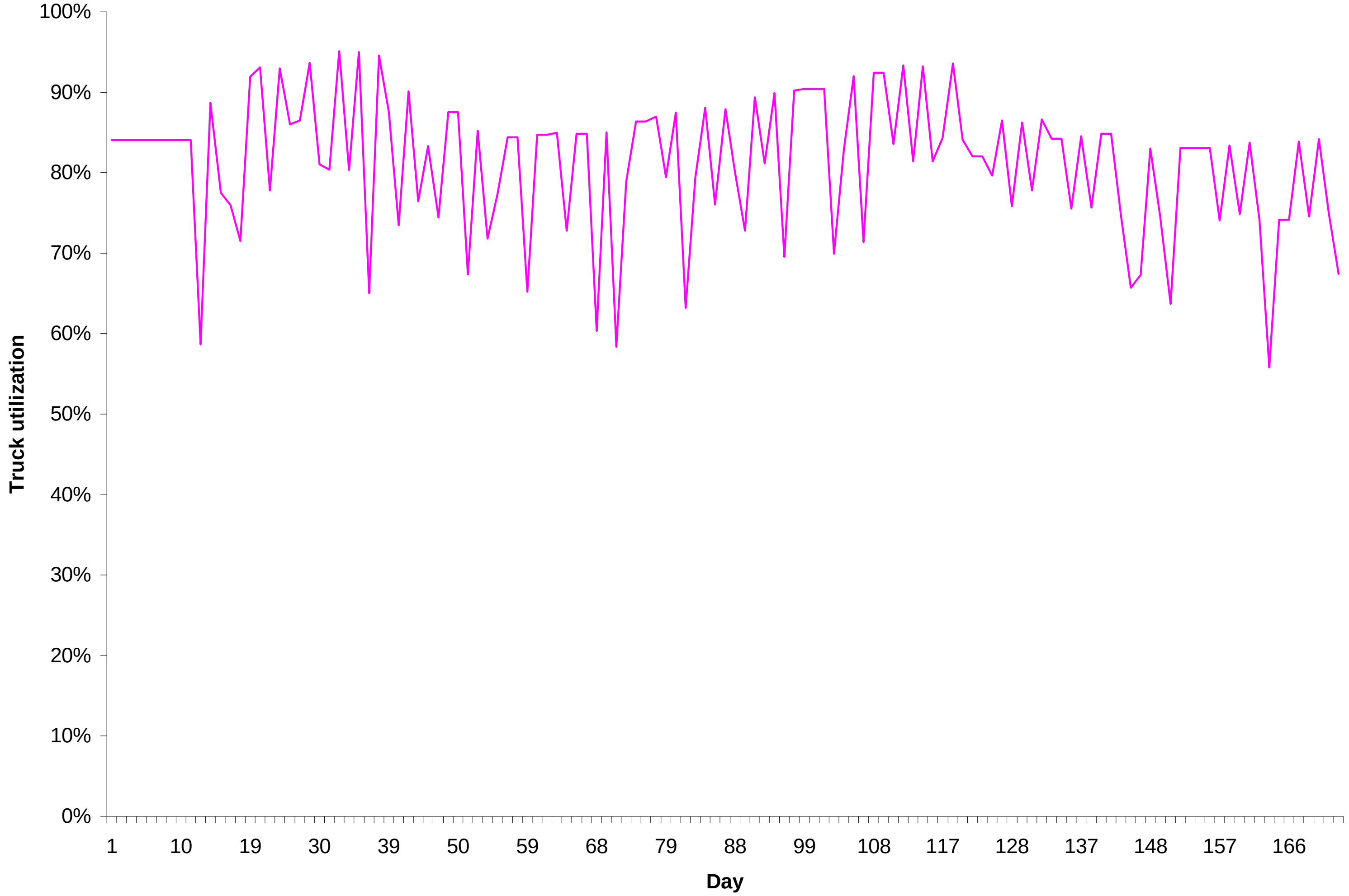


**Figure 6.20 Overall average truck utilization rate (50% land use rate)**

## 6.4 Policy 3 – Shortest Travel Time first and Longest Travel Time next, with Contours and half Loader (STT-LTT-C-HL)

Policy 3 was introduced to demonstrate the effects of loader breakdown and the system's ability to cope with this breakdown. In this particular policy, loaders 1 to 9 except Loader 5 are assigned per management Policy 1, but Loader 5 only operates every other week and can service only half as many SSLs as Loader 5 in Policy 1. This corresponds to a 6% capacity loss per week as compared to Policy 1.

### 6.4.1 Policy 3 – Results and analysis:

As discussed in section 6.1.4, Loader 5 was operated every other week to simulate loaders being out of operation for maintenance. The rest of the loaders followed the previously described Policy 1's schedule. Figure 6.22 shows the inventory level at the plant using Policy 3. The inventory level was well behaved and did not show any tendency to increase over the 6-month season as in Policies 1 and 2.

This stability of inventory occurred because Loader 5 only operates part-time, and the buildup of excess inventory at the plant is reduced. The inventory level followed the same general trend at 45% land use rate (Figure 6.23). Surprisingly, at 40% land use rate, the system was not capable of supplying sufficient loads (Figure 6.24). This capacity shortage was caused by an increase in average travel time because the procurement area increased with decreased loads at each SSL.

A real-world management policy would probably use contracts that specify the number of loads each hauling contractor will deliver each week. A contractor would typically have a loader and a given number of trucks. If the hauling contractor gets all the loads hauled before end-of-workday, for example, Thursday, then the crew may take a long weekend.

Conversely, if the weekly contract is not filled by end-of-workday Friday, the crew has to work on Saturday to fulfill the agreement. The contract will have penalty for supplying material earlier than its due date as it will increase storage requirement at the plant and a penalty for missing its due date, as the receiving facility at the plant needs to operate an extra day, increasing plant operating cost.

Figure 6.25 shows the number of trucks used under Policy 3. The square-wave oscillation in the numbers is due to the fact that Loader 5 only operates ever other week. The overall truck utilization rates were similar to Policies 1 and 2 and were 80%, 81% and 79% for 50%, 45% and 40% land use rates, respectively. Figure 6.26 shows the average truck utilization rates for 50% land use rate under this policy. The average at plant inventory was 294, 284 and 151 loads for 50%, 45% and 40% land use rates, respectively.

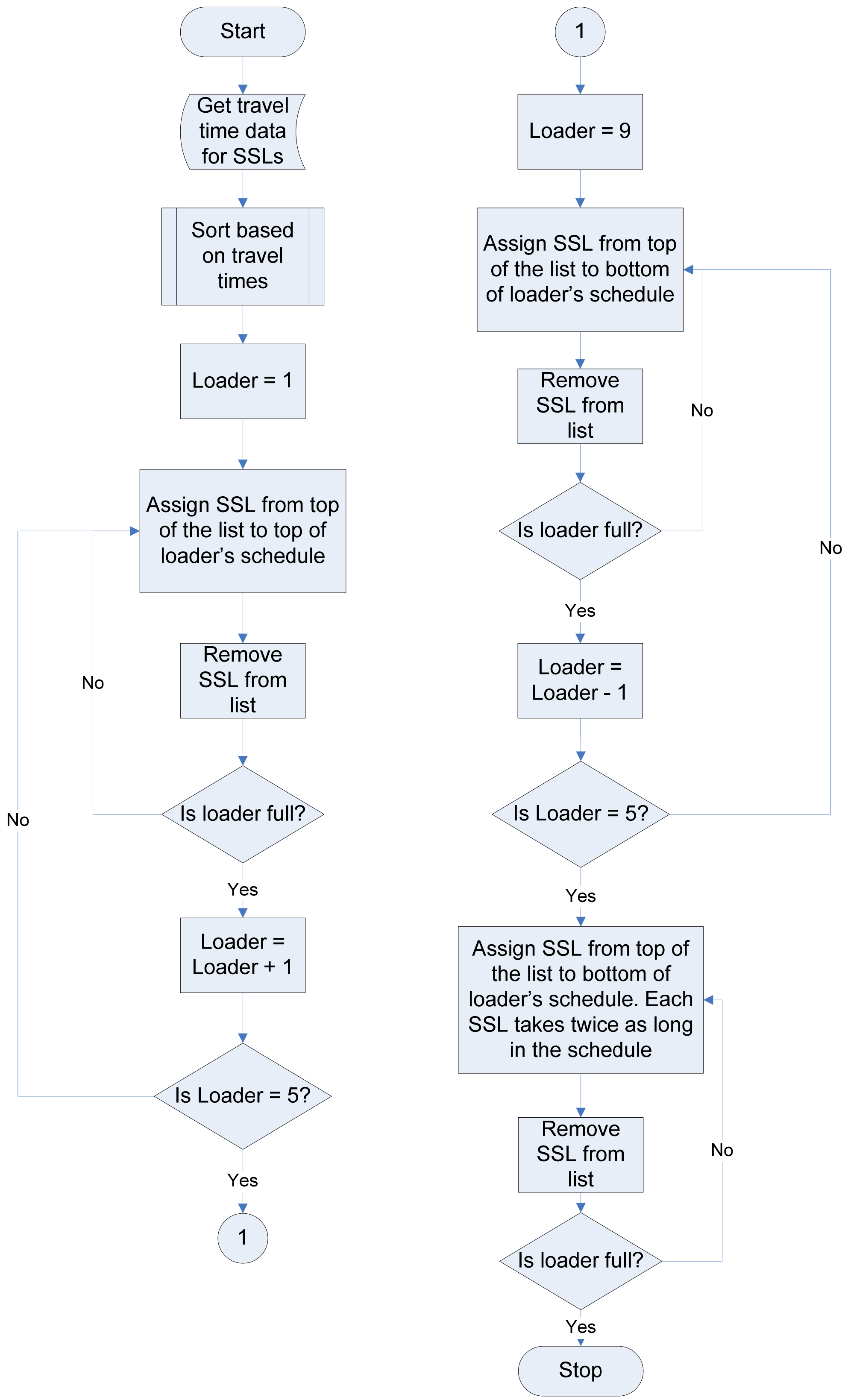


**Figure 6.21 Process flow chart for assigning SSLs to loaders under Policy 3**

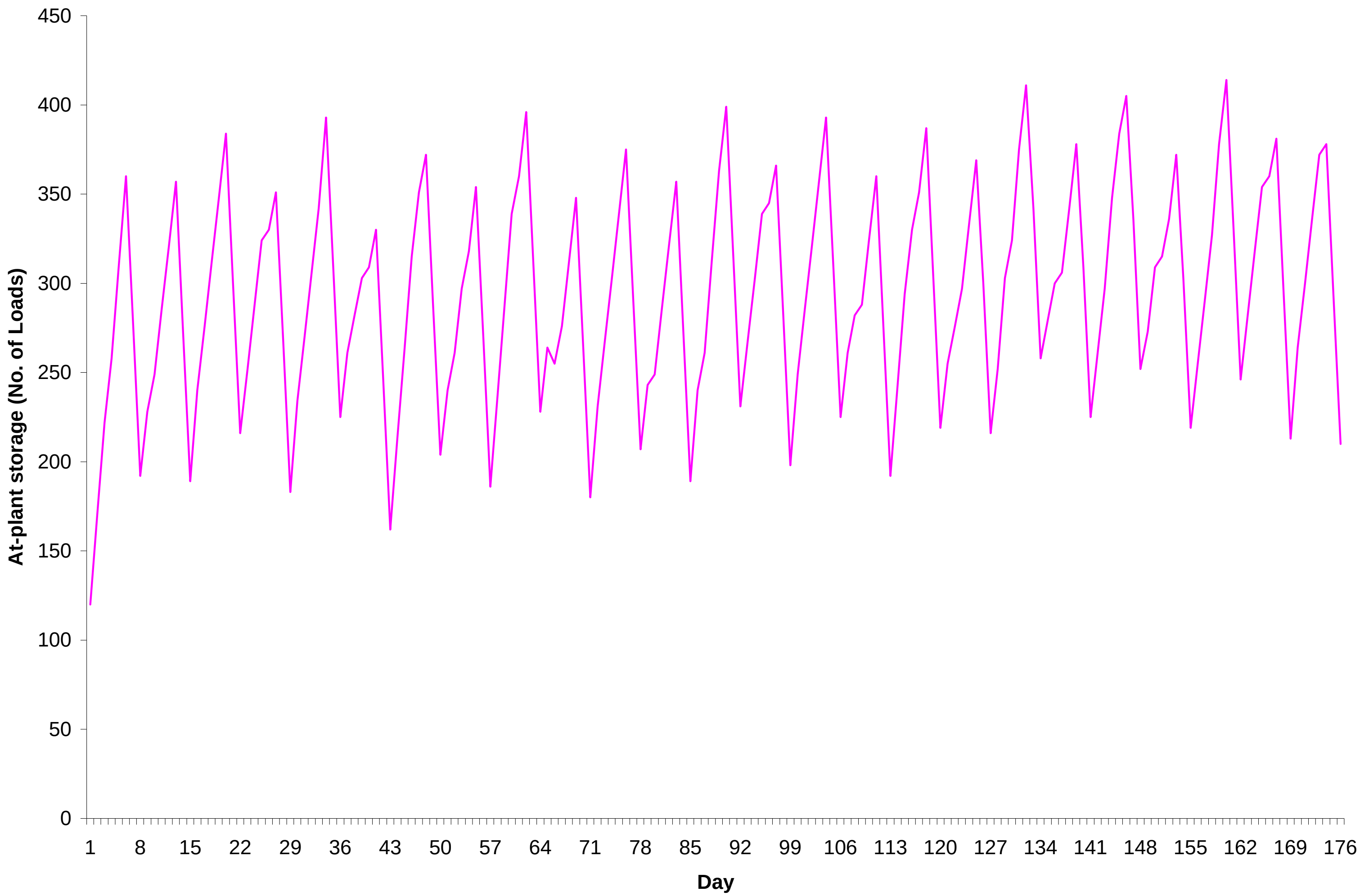


**Figure 6.22 Inventory level at the plant with 9 loaders, Policy 3, 50% land use rate**

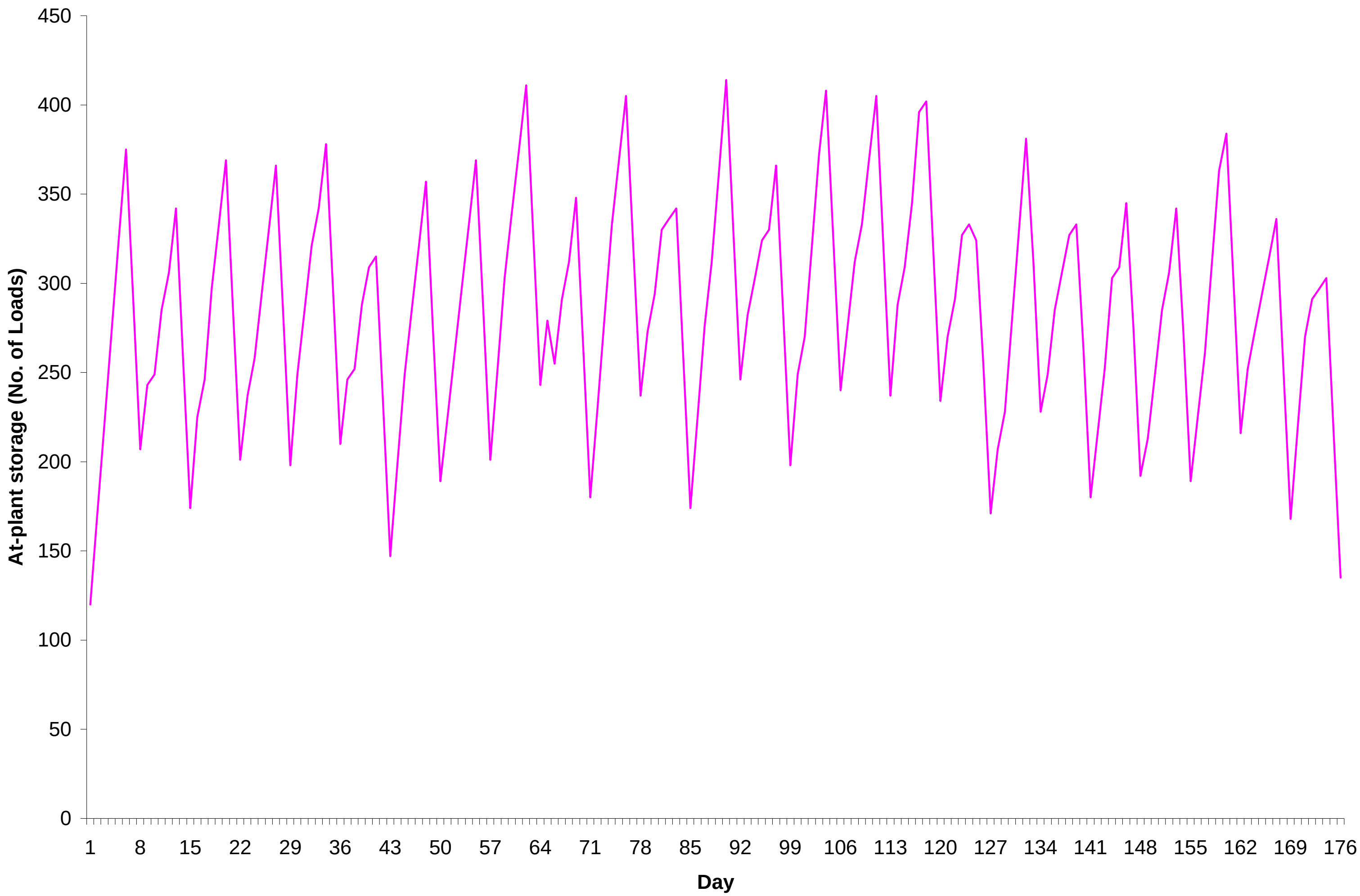


**Figure 6.23 Inventory level at the plant with 9 loaders, Policy 3, 45% land use rate**

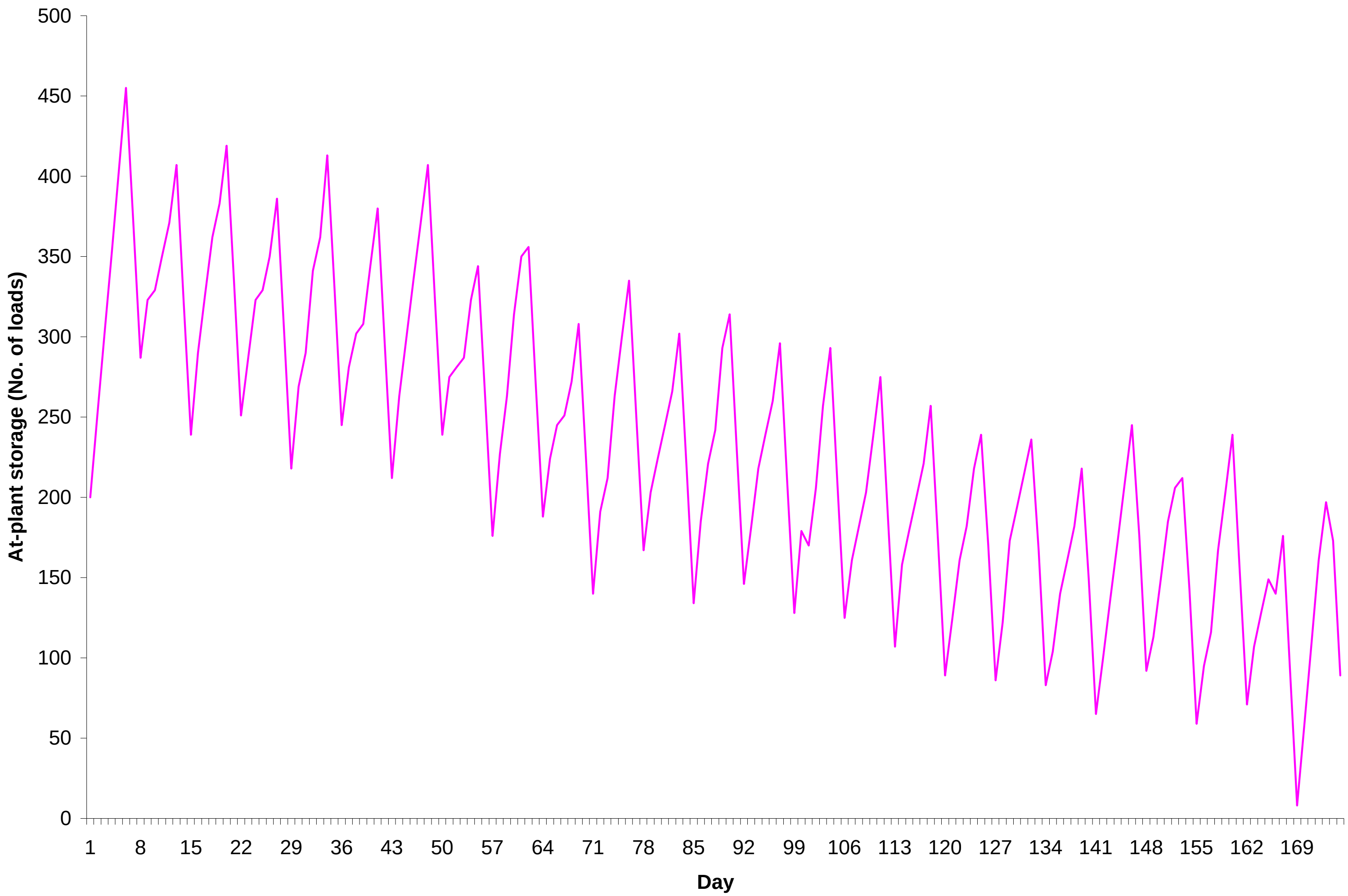


**Figure 6.24 Inventory level at the plant with 9 loaders, Policy 3, 40% land use rate**

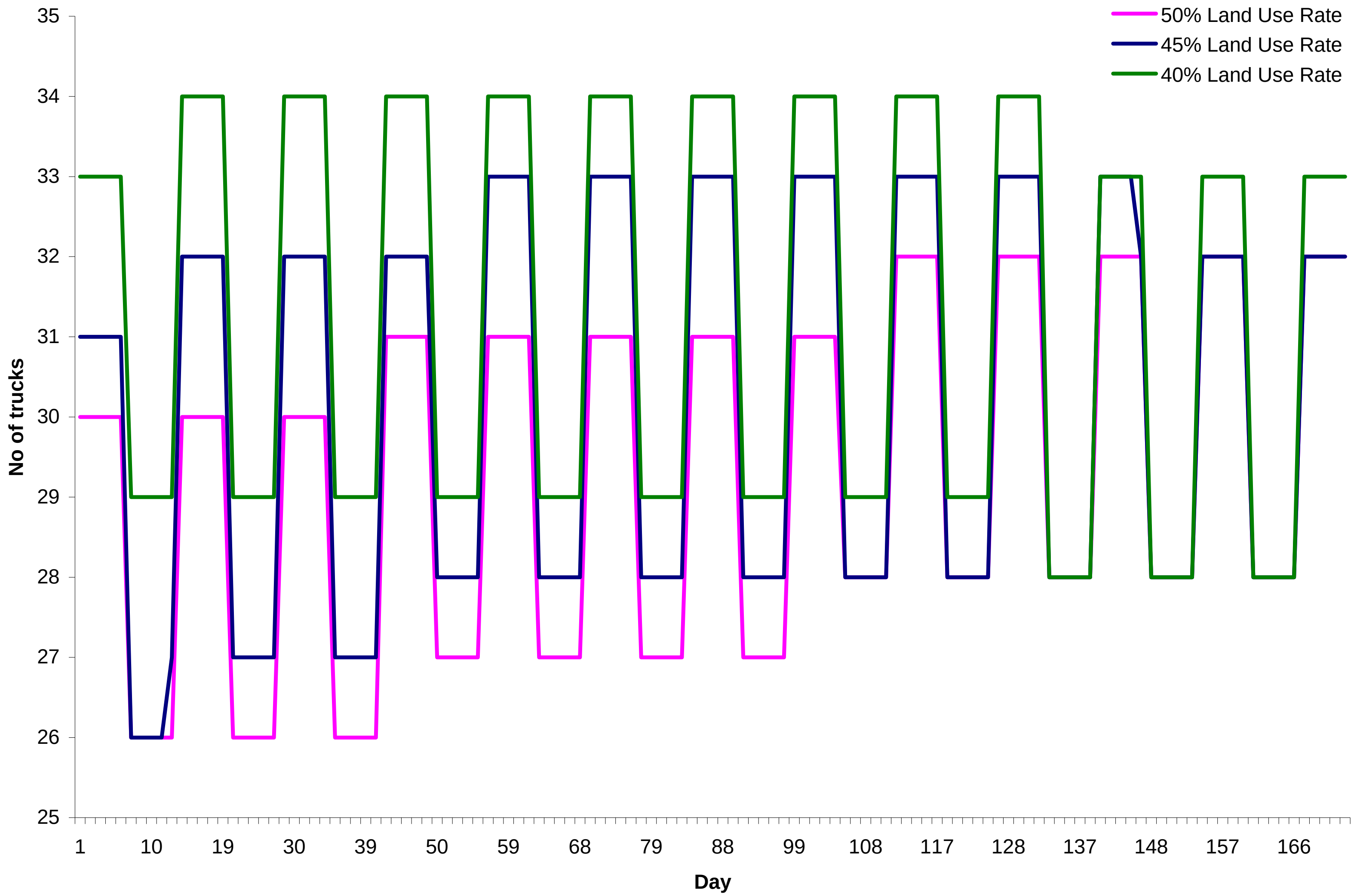


**Figure 6.25 Number of trucks used, Policy 3 as impacted by land use rates**

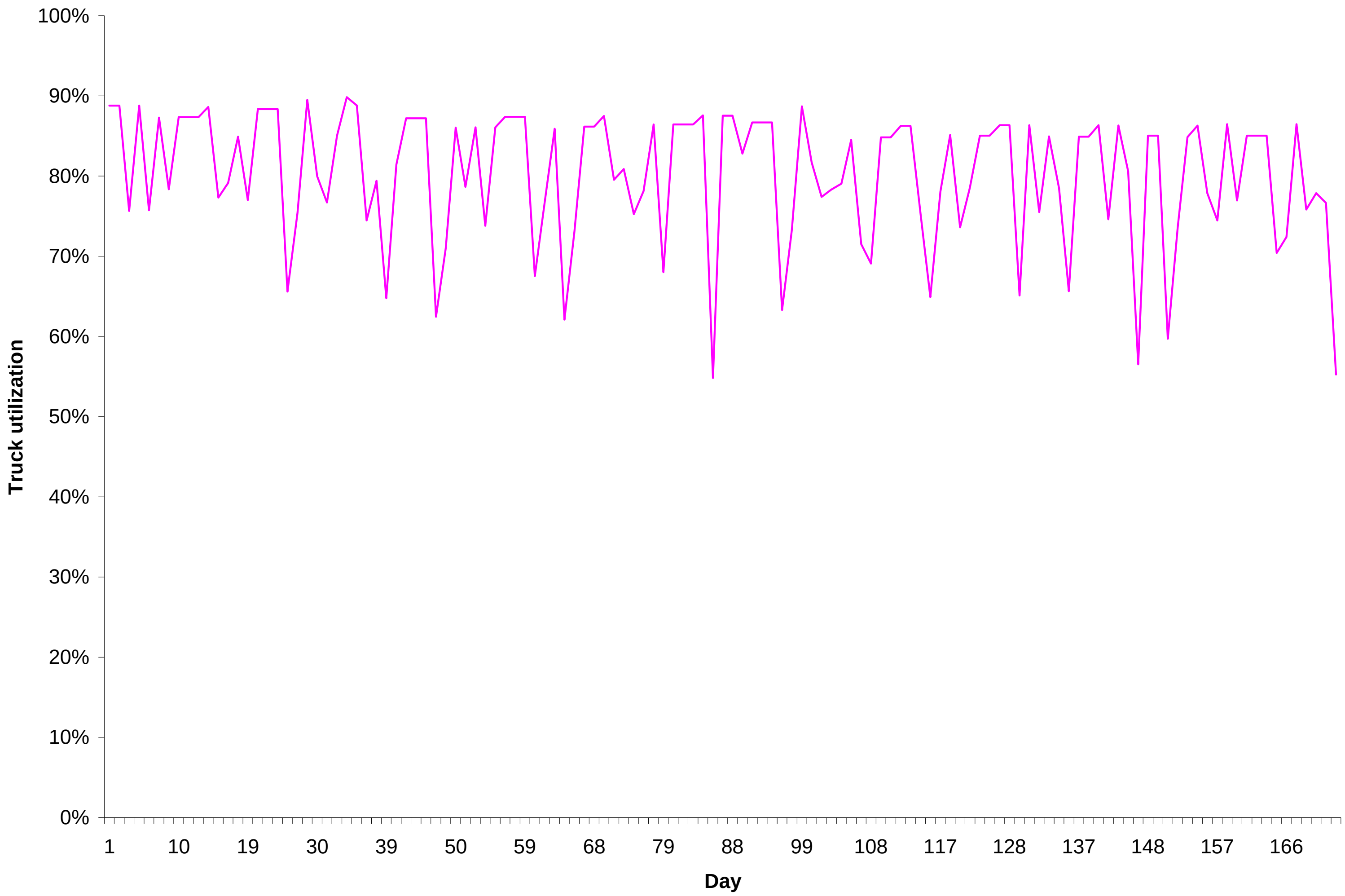


**Figure 6.26 Average truck utilization factor for Policy 3, 50% land use rate**

## 6.5 Policy 4 – Shortest Travel Time first and Longest Travel Time next, with Contours and minimum loader travel (STT-LTT-C-MLT)

Loader travel between SSLs, although not as large as truck travel between plant and SSLs, does pose significant problems due to high cost per-km move and low transport speeds, if the loader is hauled and low travel speeds if the loader is transported by a flatbed truck. Ideally, loaders should never crisscross the procurement region. But in Policies 1, 2 and 3, there is some amount of crisscrossing. To minimize this, the schedules from Policy 1 were run through a traveling salesman algorithm and the effects on crisscrossing calculated. Figure 6.27 shows the process flow diagram for determining the schedule for STT and LLT loaders using Policy 4.

### 6.5.1 Tortuosity factor

Traveling Salesman Problem (henceforth referred to as TSP) is a NP hard problem with no known optimal polynomial time algorithm to solve it. TSP algorithms need inter-SSL travel distance to calculate the order to travel between SSLs. In this study, travel distances and travel times from the plant to SSLs were computed using road network (Chapter 5). Although it is possible to calculate inter-SSL travel distances using this same technique, the presence of algorithms that exploit triangular inequality to solve TSP problems at a faster pace than other methods helped make a decision to use Euclidian distances for inter-SSL travel calculations.

Actual road travel is usually not on a straight line and this introduces an "error" when approximating real road travel distances based on Euclidean calculations. To minimize this problem, a tortuosity factor, defined as the ratio of actual road distance to Euclidian distance was computed for travel from the plant to the SSLs in SPV region.

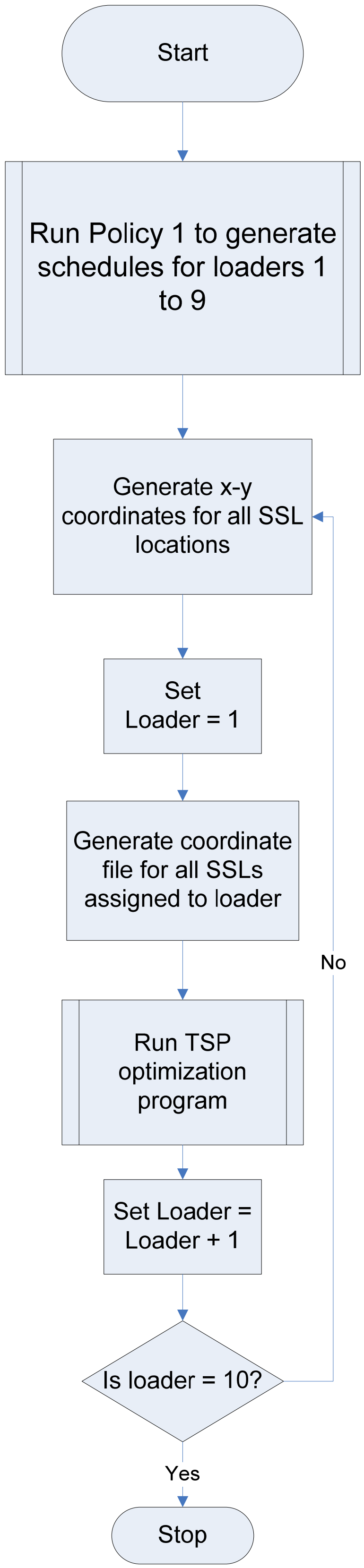


**Figure 6.27 Process flow chart for assigning SSLs to loaders under Policy 4**

The entire region was split into concentric circles, with a radius of 16 km for the innermost circle and each outer circle larger than the previous circle by 4 km (radius). Figure 6.28 shows the location of each SSL with respect to the concentric circles. Given that this factor was computed for the specific region in consideration, it was assumed that the factor remains the same for inter-SSL travel.

Figure 6.29 shows the frequency of tortuosity factor in the SPV region. The average tortuosity factor was found to be 1.31 with a standard deviation of 0.17. The tortuosity factor varied from a minimum value of 1 to a maximum value of 1.98. ArcMap (ESRI, 2005) was used to add X and Y coordinates for each SSL and this data was exported for use by the TSP program.

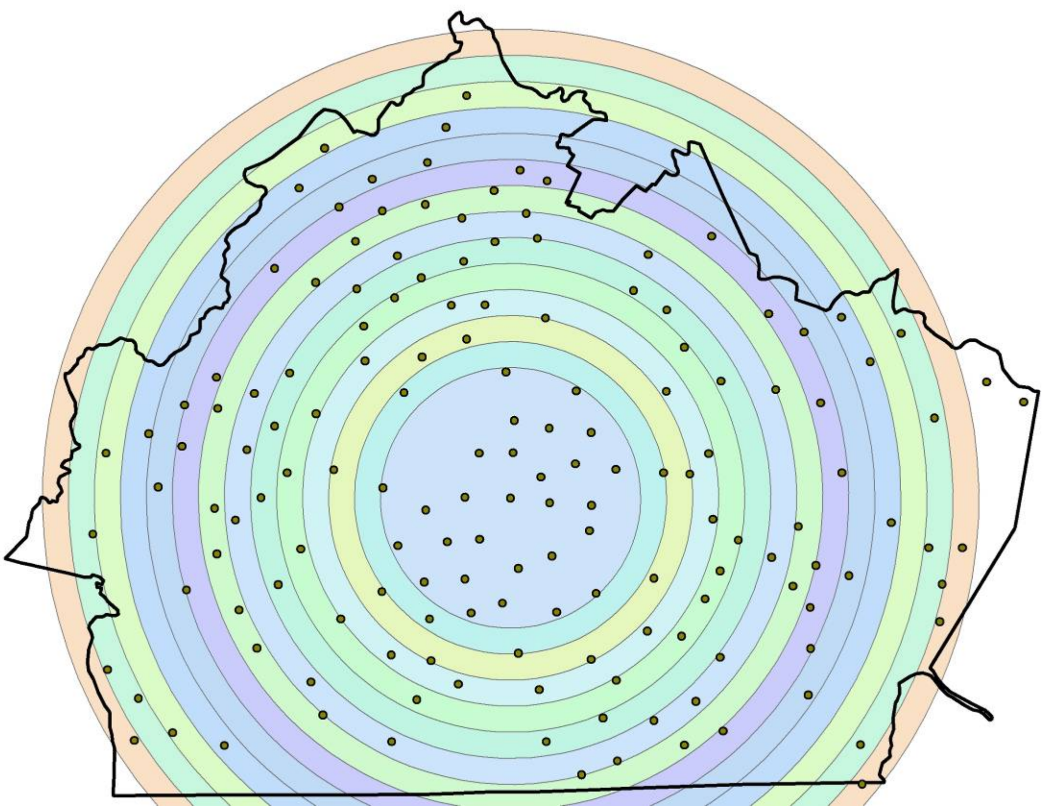

**Figure 6.28 Tortuosity calculations in SPV region**

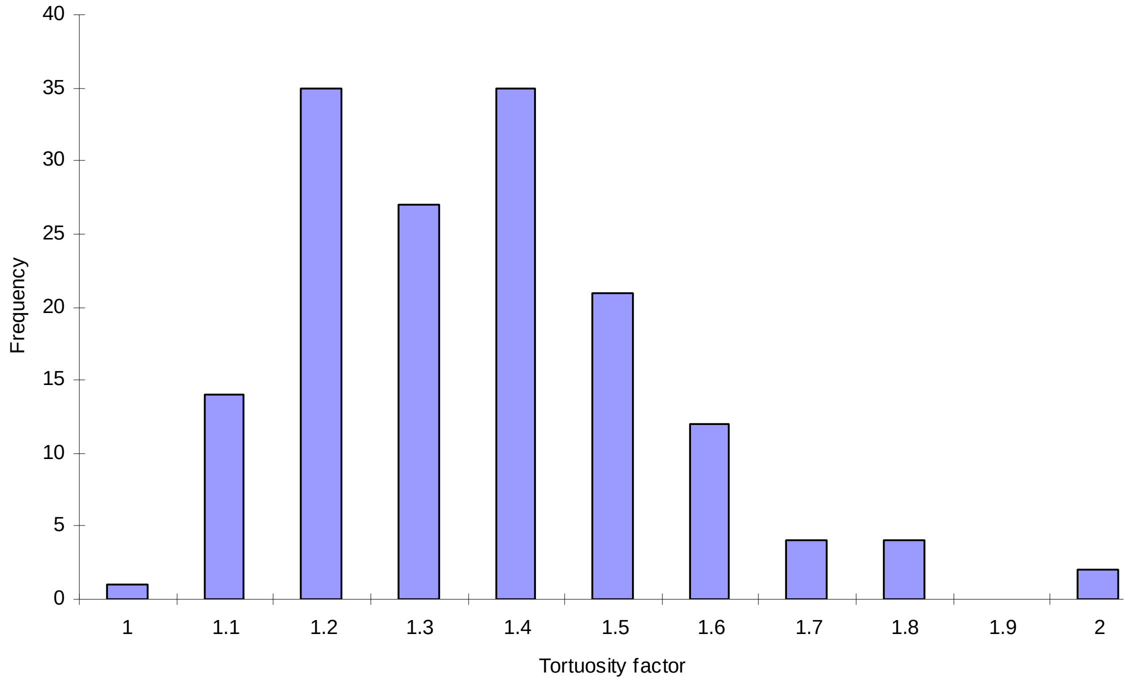


**Figure 6.29 Frequency distribution of tortuosity factor**

Concorde, a TSP solver using QSopt® linear programming solver was used to generate minimum distance Hamiltonian cycles for a given set of SSLs, using Chained-Lin-Kernighan heuristic for the TSP. Appendix A6-1 contains detailed information on running Concorde, the parameters used and the format of input data used by Concorde.

Figure 6.30 shows the resulting decrease in inter-SSL travel time when applied to SSL schedule from Policy 1 (50% land use rate). Using TSP algorithm reduced the total loader travel from 5,492 km to 2,498 km, a reduction of 55%. The same trend held for 45% and 40% land use rates (Figure 6.31 and Figure 6.32, respectively). The average reduction in inter-SSL travel was 58% (6,396 km to 2,642 km) for 45% land use and 63% (10,198 km to 3,763 km) for 40% land use rate.

The increase in travel savings can be explained by the fact that as land use rate decreased, more SSLs were used by the plant. These additional SSLs are located further away from the plant and they had a higher inter-SSL travel distances. An optimal travel path in these additional SSLs had a significant impact and resulted in a larger savings than in policies with lower land use rate.

Figure 6.33 shows the new scheduling order for Loader 3 and the resulting decrease in crisscrossing when compared to Loader 3 in Policy 1 (50% land use). Figure 6.34 shows the average truck utilization factor and the total number of trucks used by Loader 1 when operating at 50% land use rate. Although the Loader 1 used the same SSLs used by Loader 1 in Policy 1, the number of weekday moves dropped from 13 to 8. This drop was a result of changes in SSL ordering. Although the number of weekday moves was not considered a part of this study, future research may include this factor as one of the criteria as a weekday move leads to a loss of productive time for the loader and idles the associated trucks.

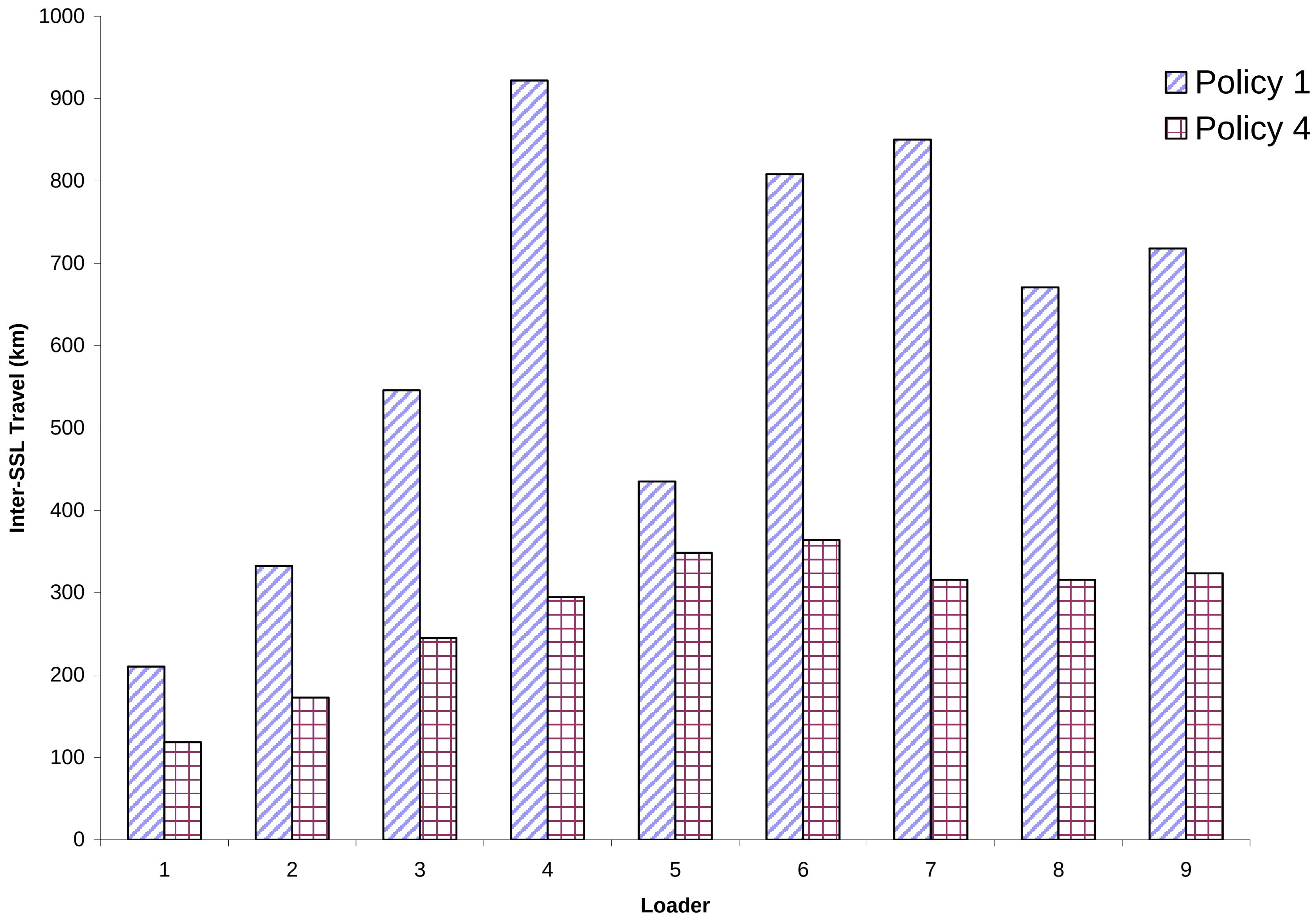


**Figure 6.30 Reduction in inter-SSL travel in Policy 1 vs. Policy 4, 50% land use rate**

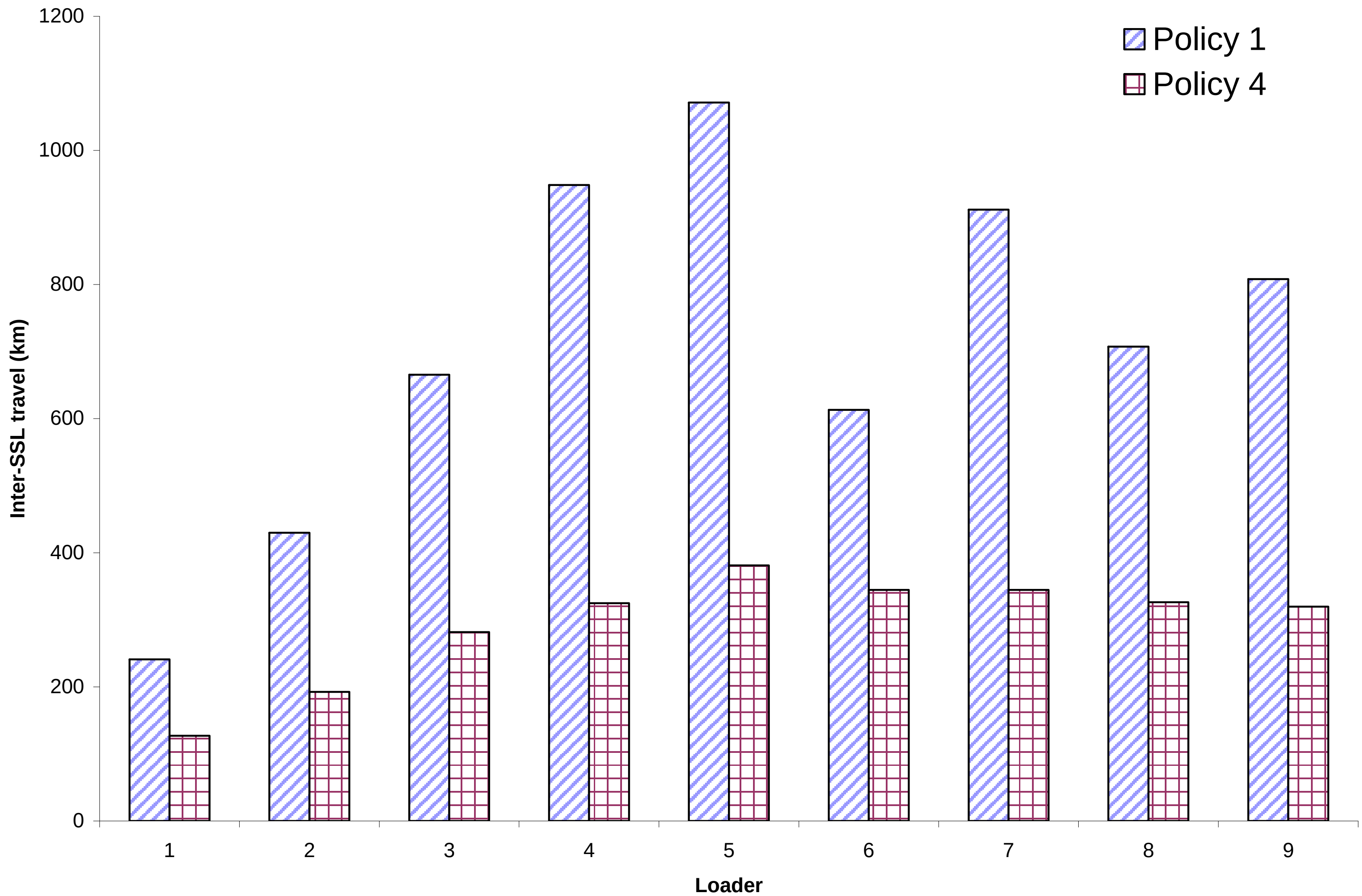


**Figure 6.31 Reduction in inter-SSL travel in Policy 1 vs. Policy 4, 45% land use rate**

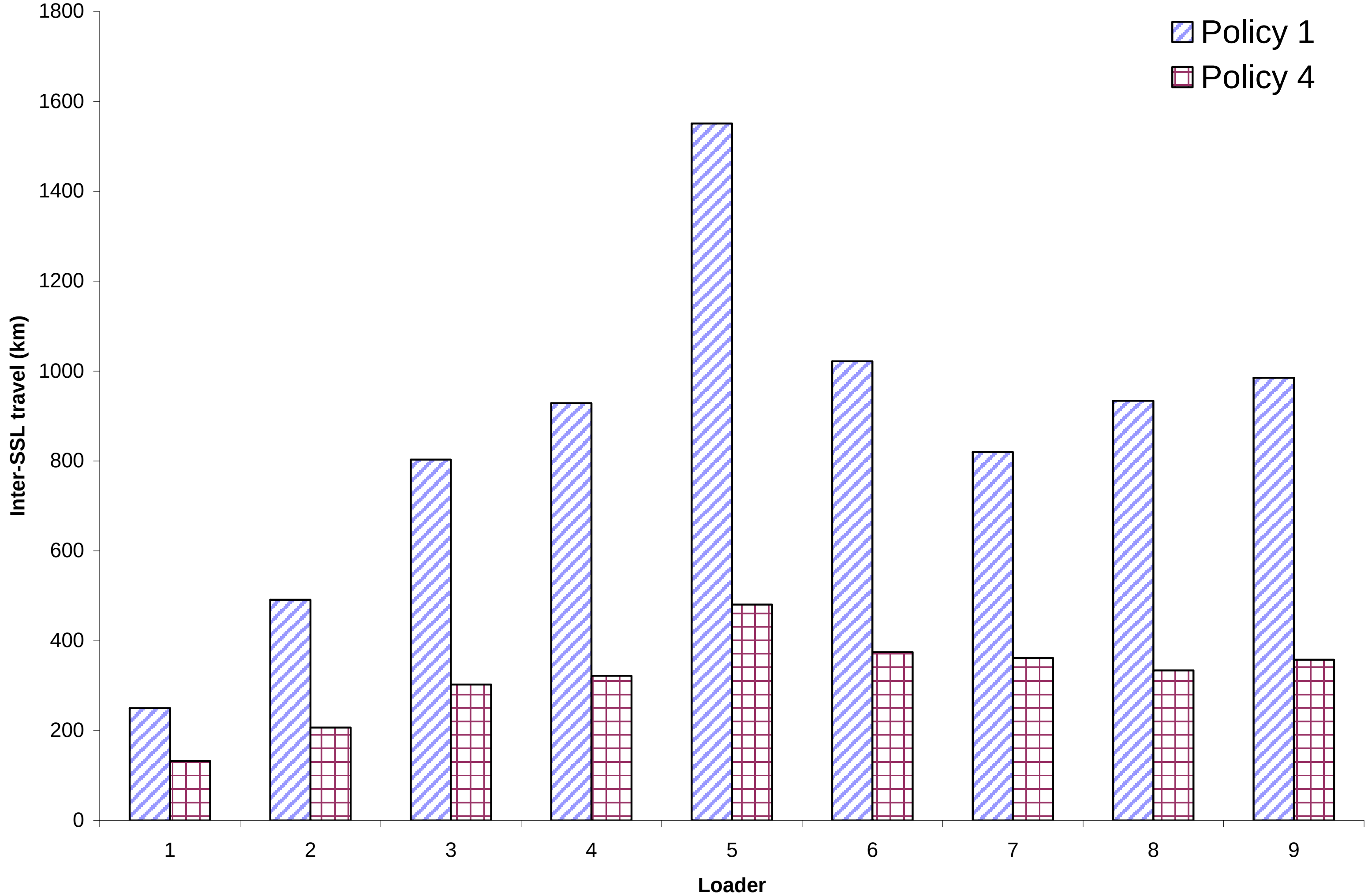


**Figure 6.32 Reduction in inter-SSL travel in Policy 1 vs. Policy 4, 40% land use rate**

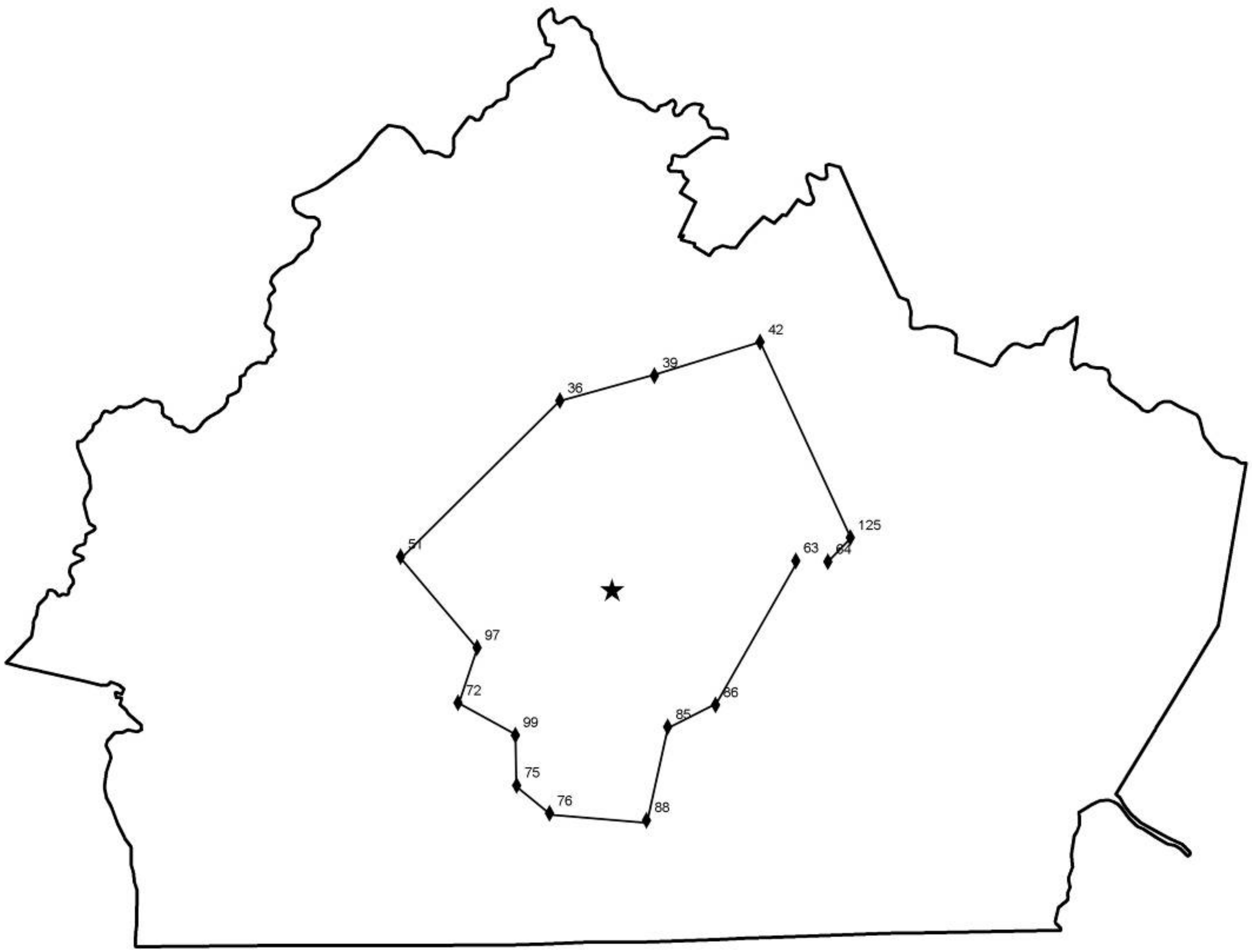


**Figure 6.33 Schedule for Loader 3, Policy 4, 50% land use rate. SSL order is 63, 86, 85, 88, 76, 75, 99, 72, 97, 51, 36, 39, 42, 125, 64.**

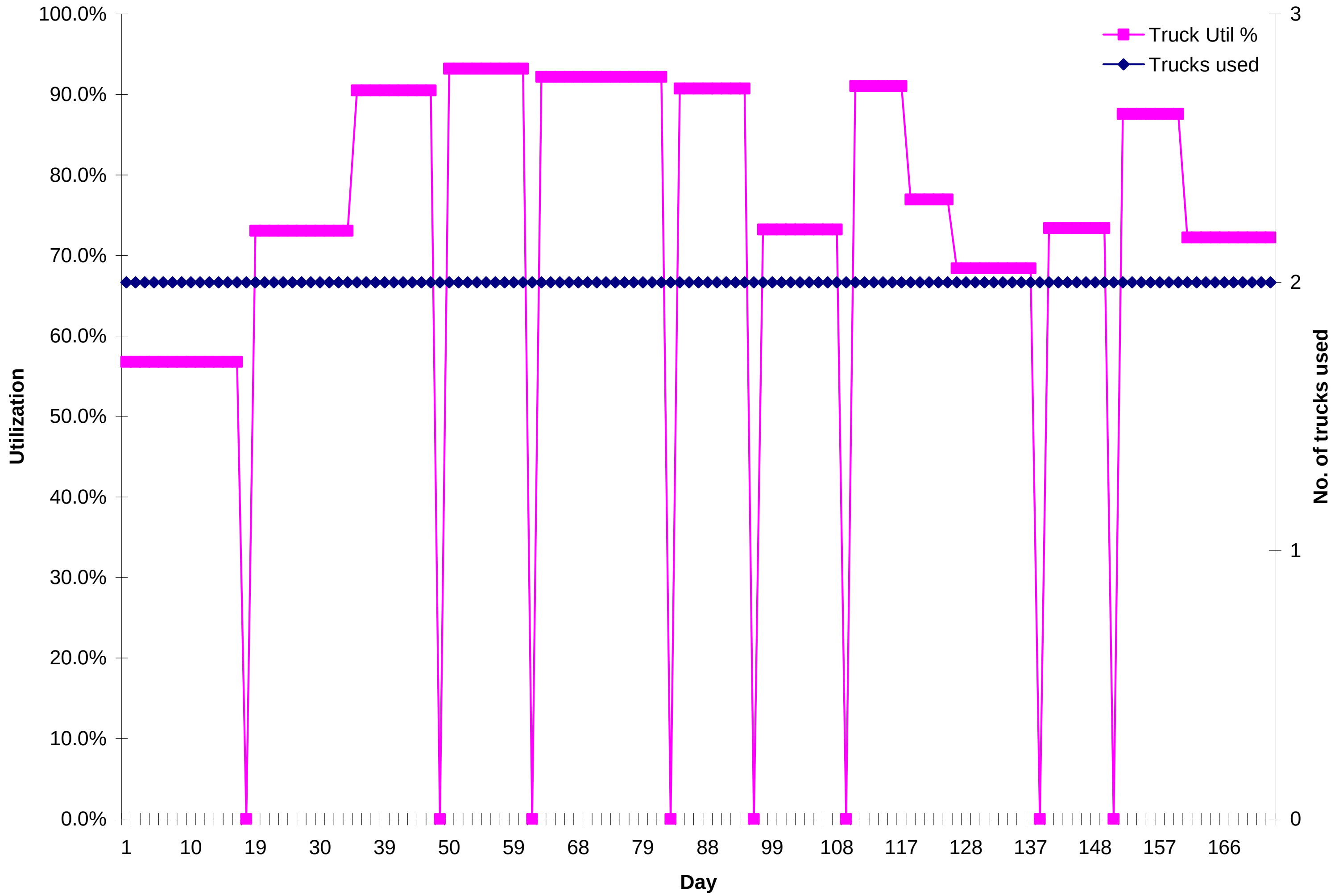


**Figure 6.34 Truck utilization and number of trucks used by Loader 1, Policy 4, 50% land use rate**

Figure 6.35 shows the comparison between at-plant storage when operating under Policy 4 and Policy 1 (50% land use rate). The at-plant inventory level in Policy 4 does not vary significantly from Policy 1. Figure 6.36 shows the overall truck utilization factor for Policy 4 when operating at 50% land use rate. The overall average truck utilization factor for Policy 4 was 81%, 80% and 79% for 50%, 45% and 40% land use rates, respectively. These utilization factors remained the same as the utilization factors for Policy 1.

Figure 6.37 shows the total number of trucks used by Policy 4 as the season progressed. The maximum number of trucks used was 32 and the minimum number of trucks used was 30. This truck use also matched usage numbers from Policy 1. Figure 6.38 shows the total number of trucks used by policies 1 and 4, when operating at 45% land use rate while Figure 6.39 shows the total number of trucks used by policies 1 and 4, when operating at 40% land use rates. The numbers remained unchanged from Policy 1. One drawback to this policy is the constant change in the number of trucks required by a loader. Figure 6.40 shows the variation in truck demand by Loader 2 to illustrate this point.

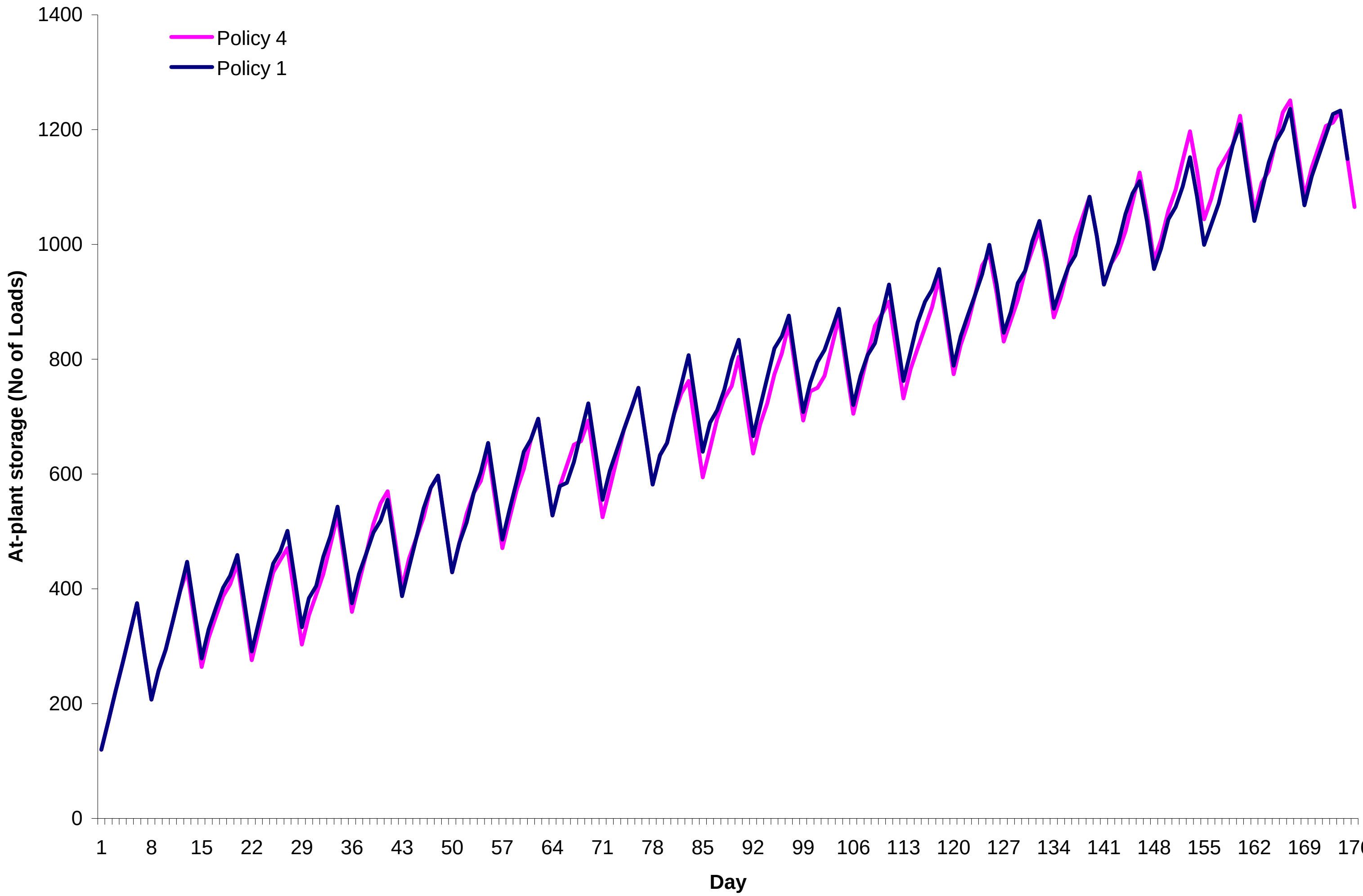


**Figure 6.35 Inventory at the plant with 9 loaders, Policy 1 and 4, 50% land use rate**

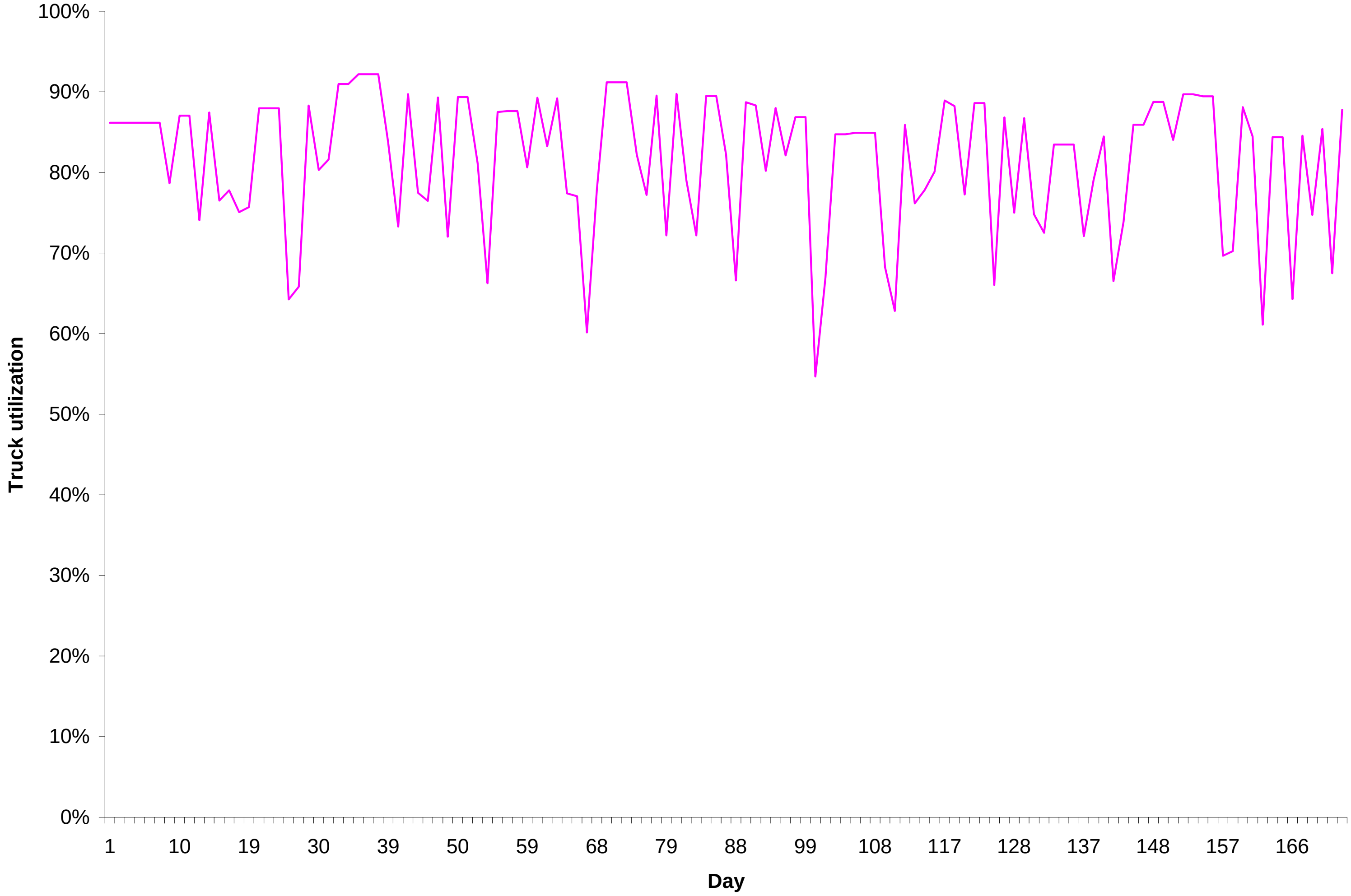


**Figure 6.36 Average truck utilization, Policy 4, 50% land use rate**

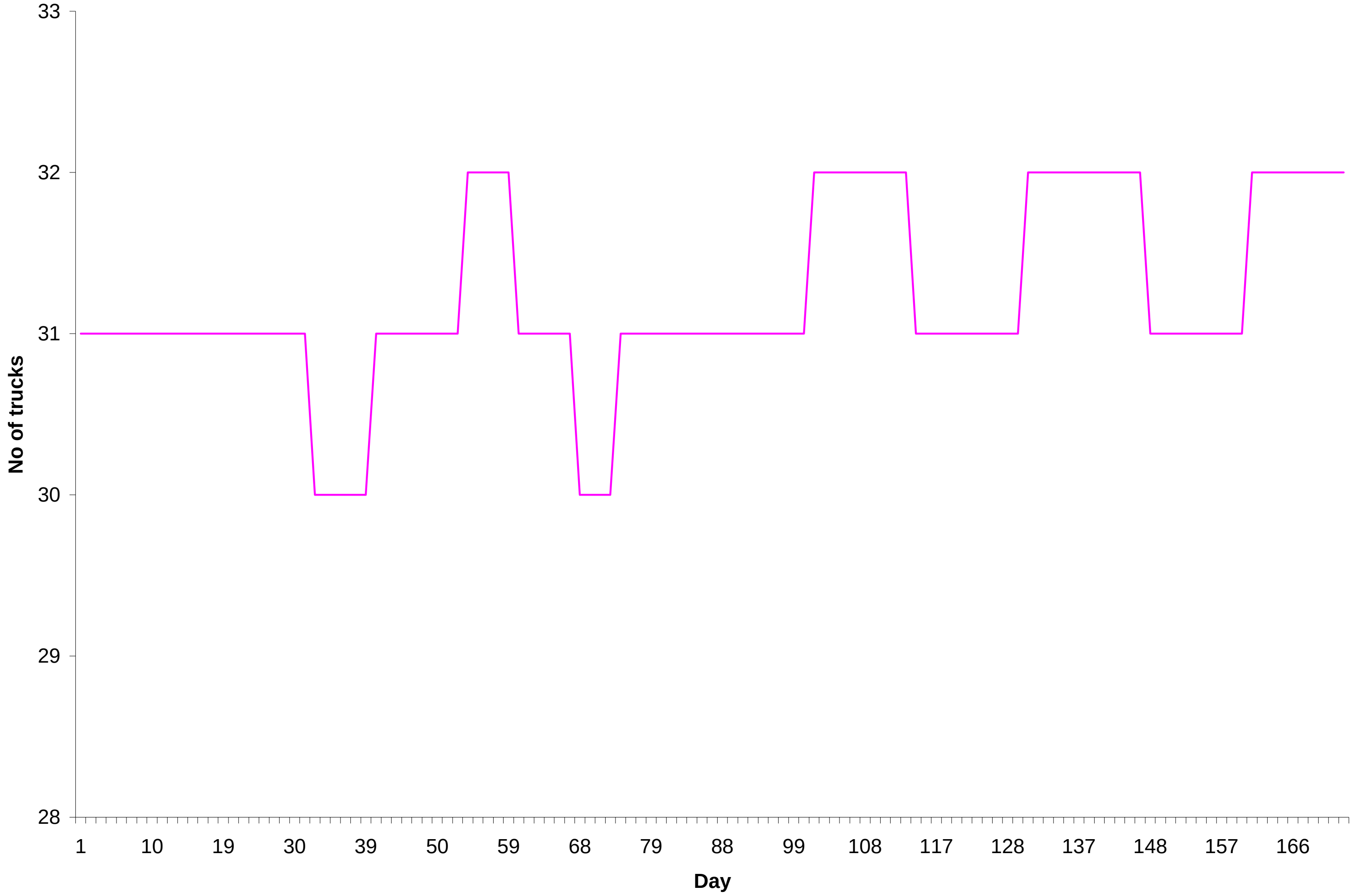


**Figure 6.37 Total number of trucks used, Policy 4, 50% land use rate**

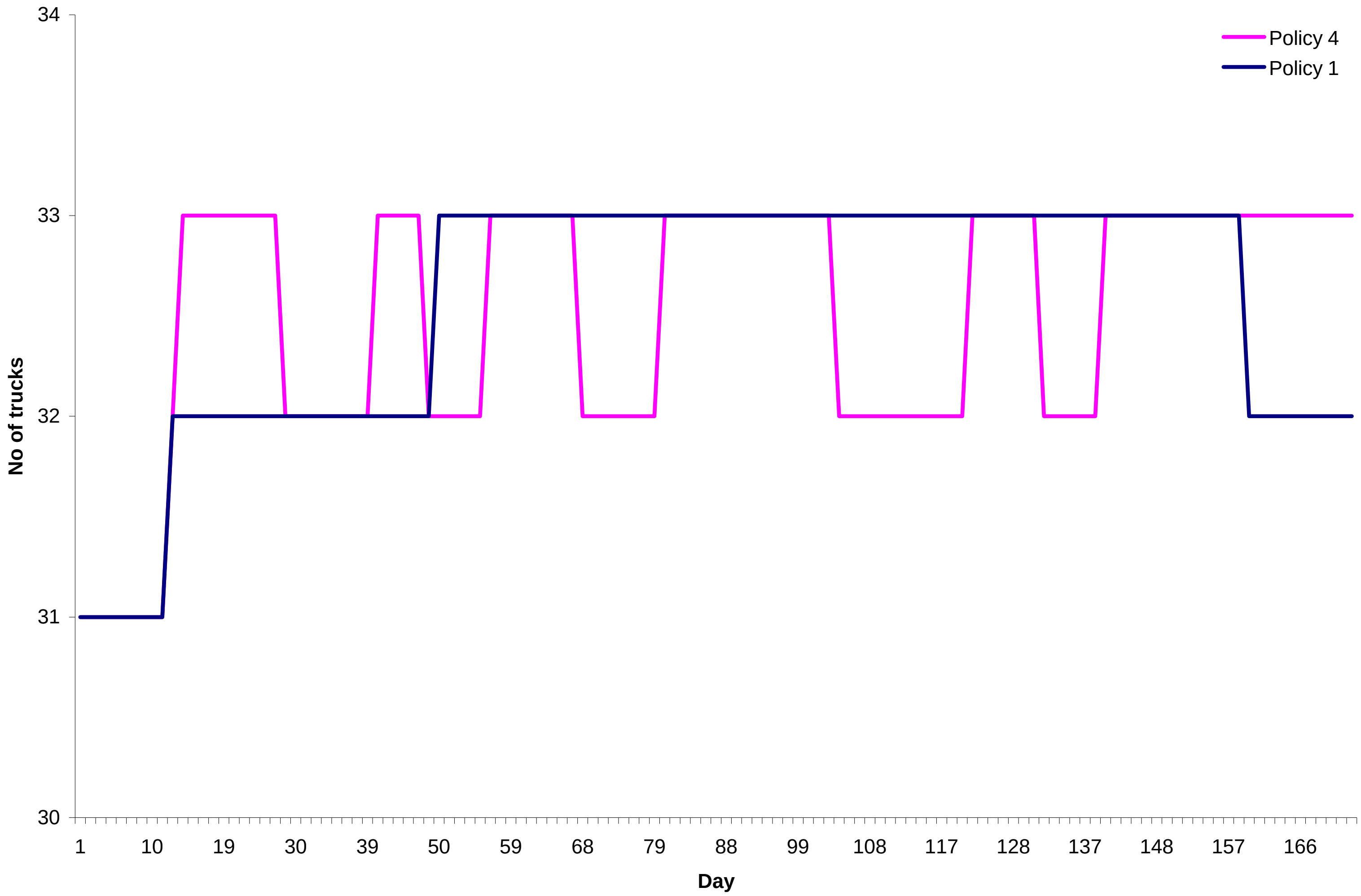


**Figure 6.38 Total number of trucks used by Policy 1 and 4, 45% land use rate**

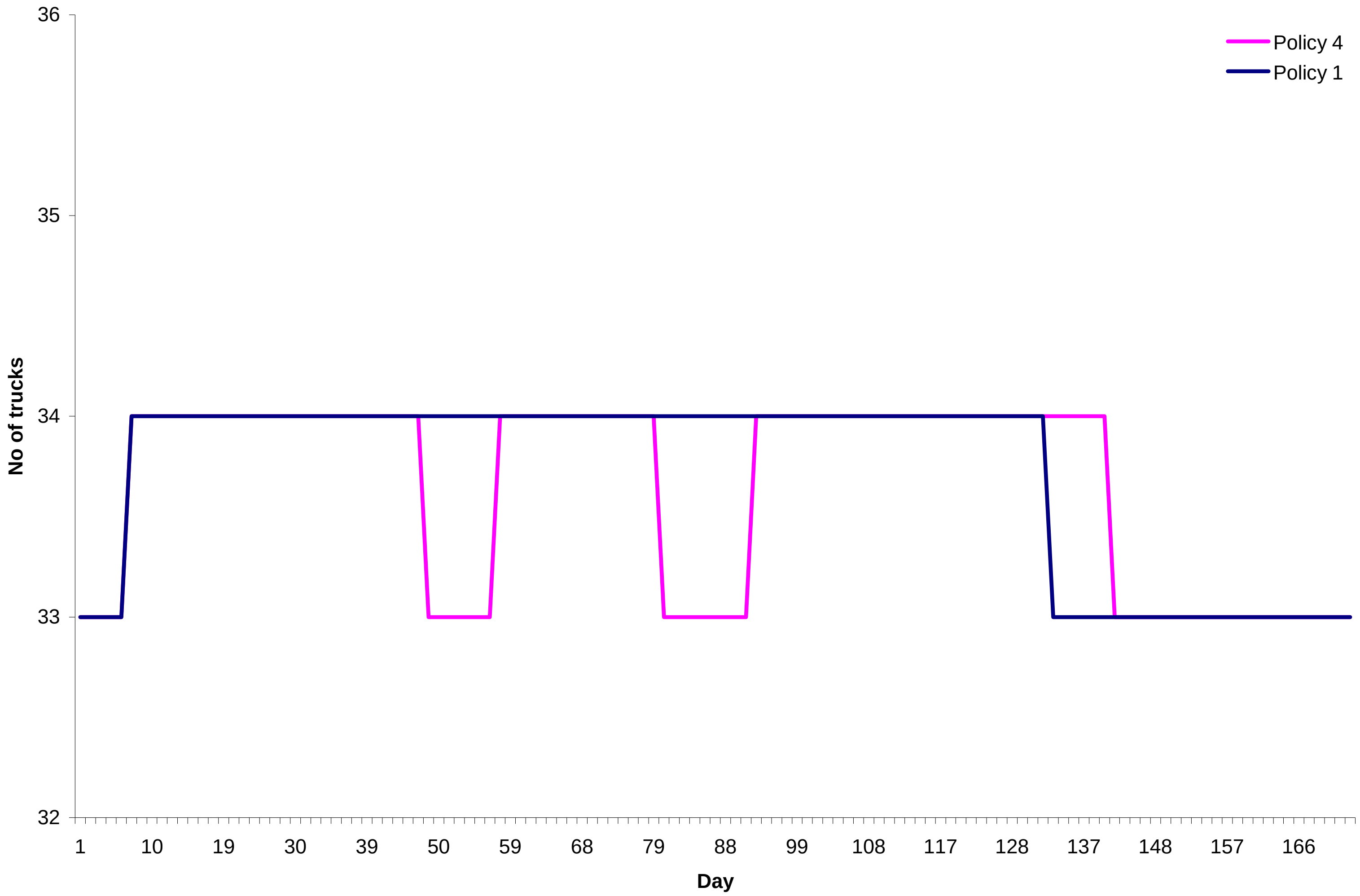


**Figure 6.39 Total number of trucks used by Policy 1 and 4, 40% land use rate**

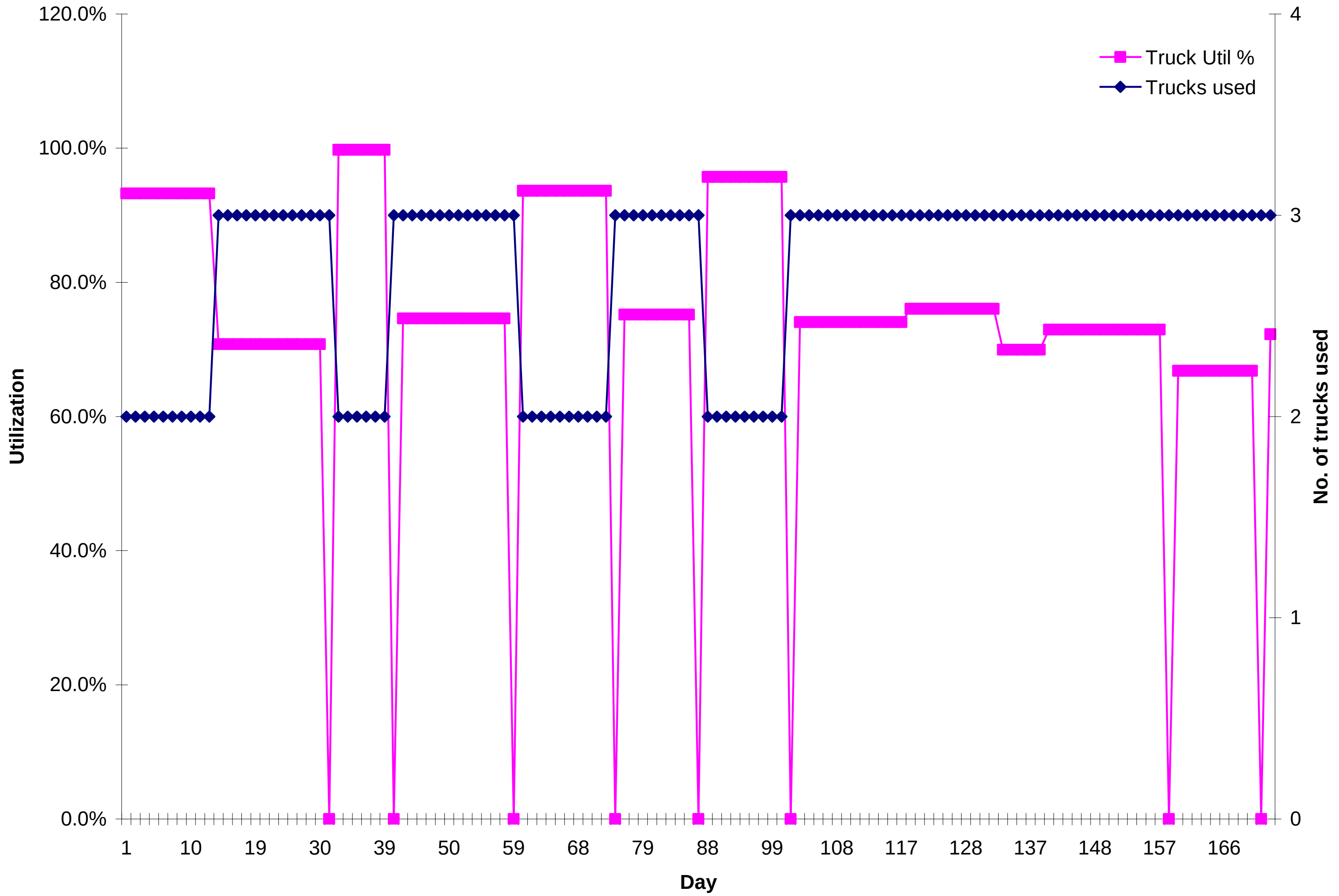


**Figure 6.40 Truck utilization and number of trucks used by Loader 2, Policy 4, 50% land use rate**

### 6.5.2 Policy 4 – Results and analysis:

As described in section 6.2, loaders in Policy 1 do crisscrossing across the region as they travel from one SSL to the next (Fig 6.21). This crisscrossing costs the plant additional expense. Policy 4 places an additional constraint on Policy 1 by specifying that the order of travel for a loader. The order should minimize total inter-SSL travel distance. This constraint forces the loaders to follow a minimum total distance Hamiltonian cycle or more commonly referred to as optimal Traveling Salesman Problem (TSP) cycle. In Policy 4, each loader's schedule from Policy 1 is run through a TSP algorithm to calculate the order of travel from one SSL to the next. This rearrangement of schedules destroys the STT/LTT structure from Policy 1.

## 6.6 Policy 5 – Sector based loader assignment

In Policy 5, the procurement region was split into five sectors and two loaders were assigned to each (except Sector 5 which had only Loader 9). One of the sector loaders starts from a SSL close to the plant and the other starts from a SSL close to the boundary. The STT and LTT rules were not implemented as a TSP algorithm will destroy such a implementation. A minimum cost Hamiltonian path was constructed in each sector to calculate path of least inter-SSL travel distance for the loaders. Figure 6.41 shows the process flow diagram for determining the sequence for SSLs under this policy. Figure 6.42 shows Policy 5 when applied to the SSLs in SPV region. Figure 6.43 shows the available loads split between sectors.

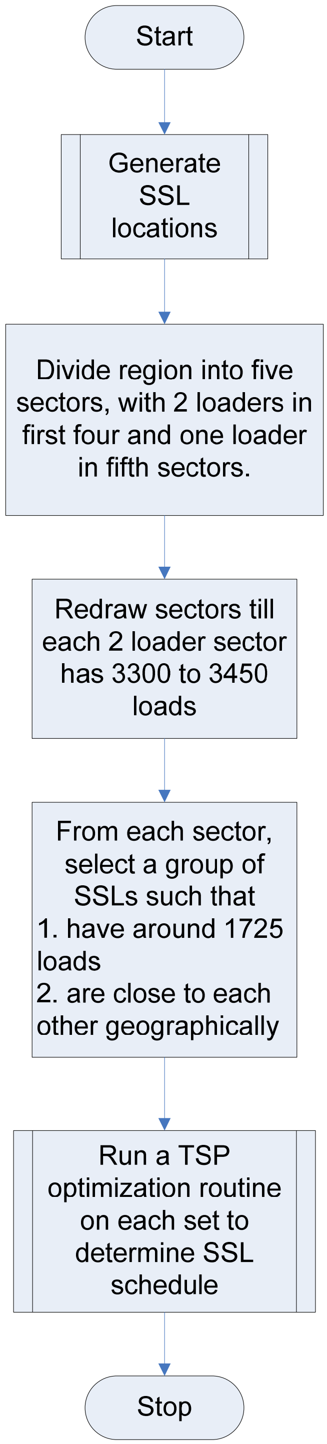


**Figure 6.41 Process flow chart for assigning SSLs to loaders under Policy 5**

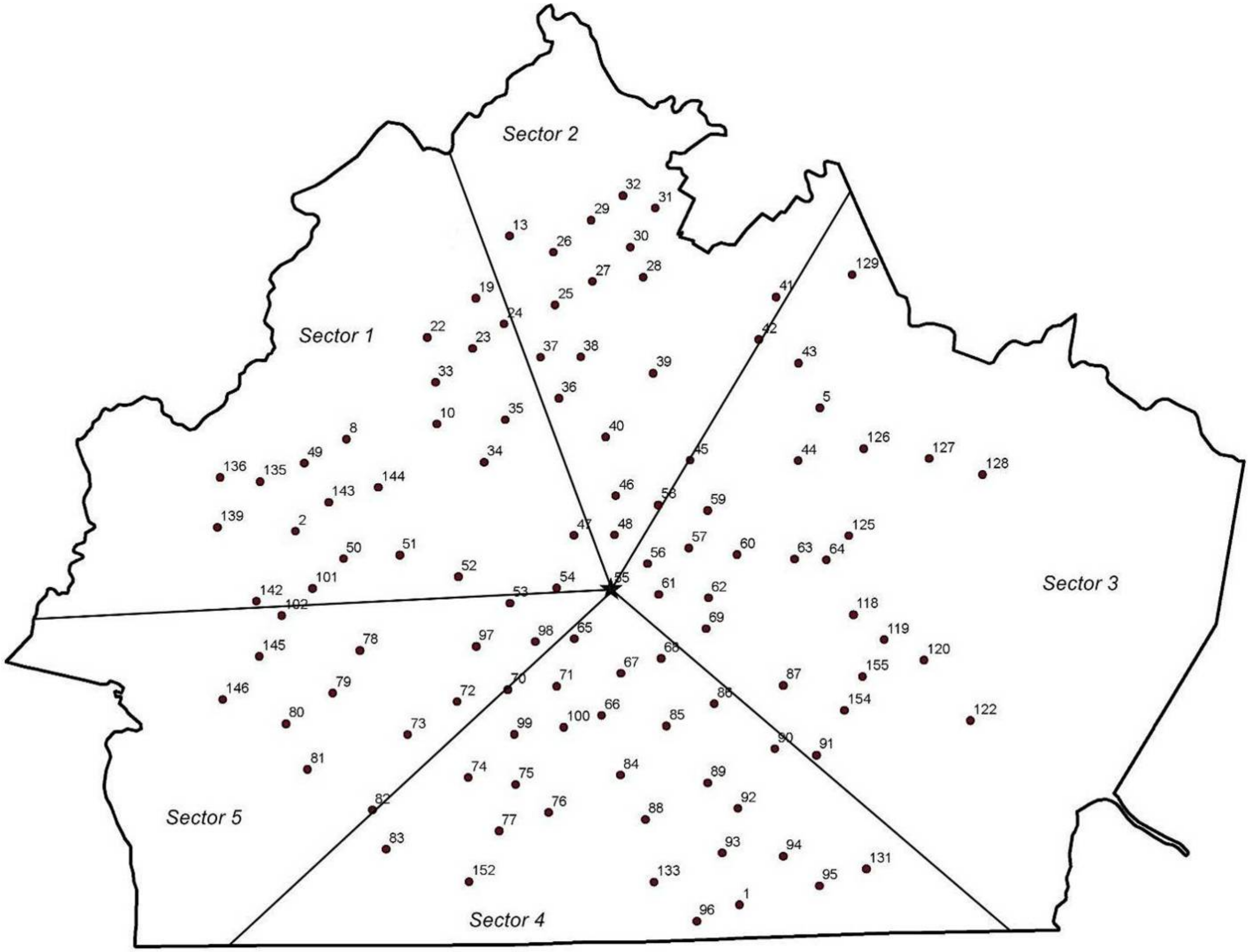


**Figure 6.42 Five sectors defined for management Policy 5 (The numbers represent the SSL numbers used in this analysis)**

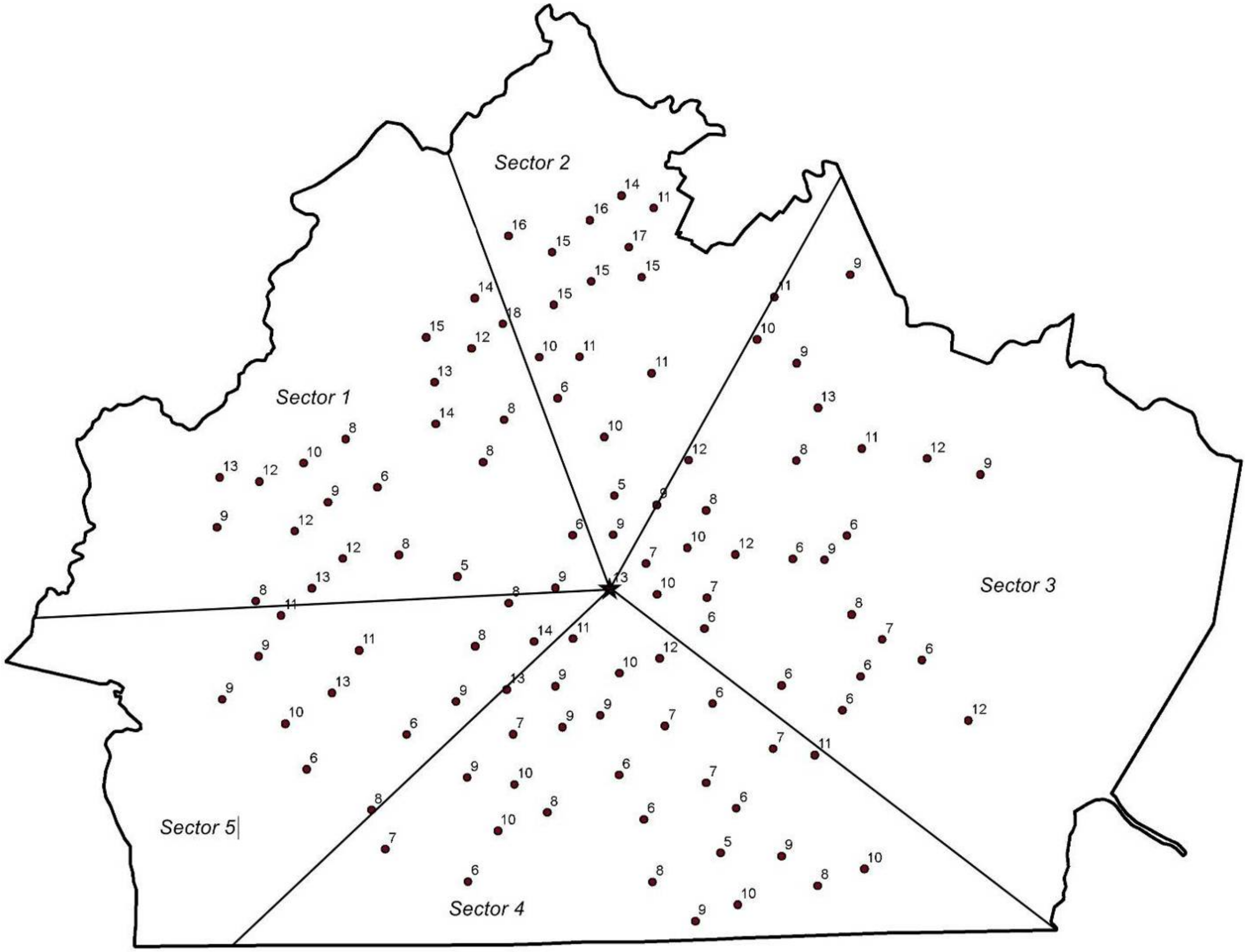


**Figure 6.43 Loads available in five sectors defined for management Policy 5 (The numbers represent the number of days required to haul all loads from a given SSL)**

Each sector in Policy 5 was divided into two, with one part consisting of SSLs close to the plant and another part consisting of SSLs closer to the outer boundary. Concorde was then used to generate optimal minimum travel distance Hamiltonian cycle in each part. This process was repeated for all other sectors, except Sector 5, which had only one loader. All SSLs in Sector 5 was included into Loader 9 and the TSP problem was solved.

Figure 6.44 shows this split in sectors for 50% land use rate along with the resulting optimal Hamiltonian cycle. The same process was repeated for 45% and 40% land use rate. Each loader was then scheduled either as a STT or a LTT, depending on the sub sector. For example, in Sector 2, the loader closest to the plant started from SSL 55, then to 48, 46, 40, 36, 37, 25, 38, 39, 41, 42, 58 before returning to SSL 55. The sequence of SSLs from 55 to 25 followed SST rule within the sequence. Effort was made to stick to STT or LTT rule as much as possible.

Figure 6.45 and Figure 6.46 show the truck utilization and number of trucks used by Loaders 3 and 4 operating in Sector 2 in Policy 5, with 50% land use rate. The number of trucks used by Loader 3 varies from two to four trucks, while the number of trucks used by Loader 4 remains steady at four. This pattern held for Sectors 1 and 3. In Sector 4, Loader 7's truck usage varied from two to three trucks, while Loader 8's truck usage varied from three to four. This was due to the fact that in Sector 4, SSLs in the sub sector closer to the plant had a flat distribution and the Loader 7 was able to operate with SSLs requiring two and three trucks without using the SSLs with four truck requirement.

Figure 6.47 shows the average truck utilization for Policy 5 at 50% land use rate. The average truck utilization was 81%, 80% and 80% for 50%, 45% and 40% land use rates, respectively. These average truck utilization rates were comparable to other policies. Figure 6.48 shows the at-plant storage for Policies 1 and 5 with 9 loaders (50% land use rate). The inventory level in Policy 5 lags behind the inventory level in Policy 1 by a very small amount. Figure 6.49 shows the inventory level at the plant in Policies 4 and 5 with nine loaders (50% land use rate). Again, the inventory level in Policy 5 lags inventory level in Policy 4 by a very small amount.

Figure 6.50 shows the total number of trucks used in Policy 5. The number of trucks used varies significantly during the six month season in this policy than all other policies, except Policy 2. The maximum number of trucks used was 34, 36 and 37 trucks for 50%, 45%, and 40% land use rate, respectively. The minimum number of trucks used was 27, 29, and 30 trucks for 50%, 45%, and 40% land use rate, respectively. The idling of 7 trucks was still less than Policy 2.

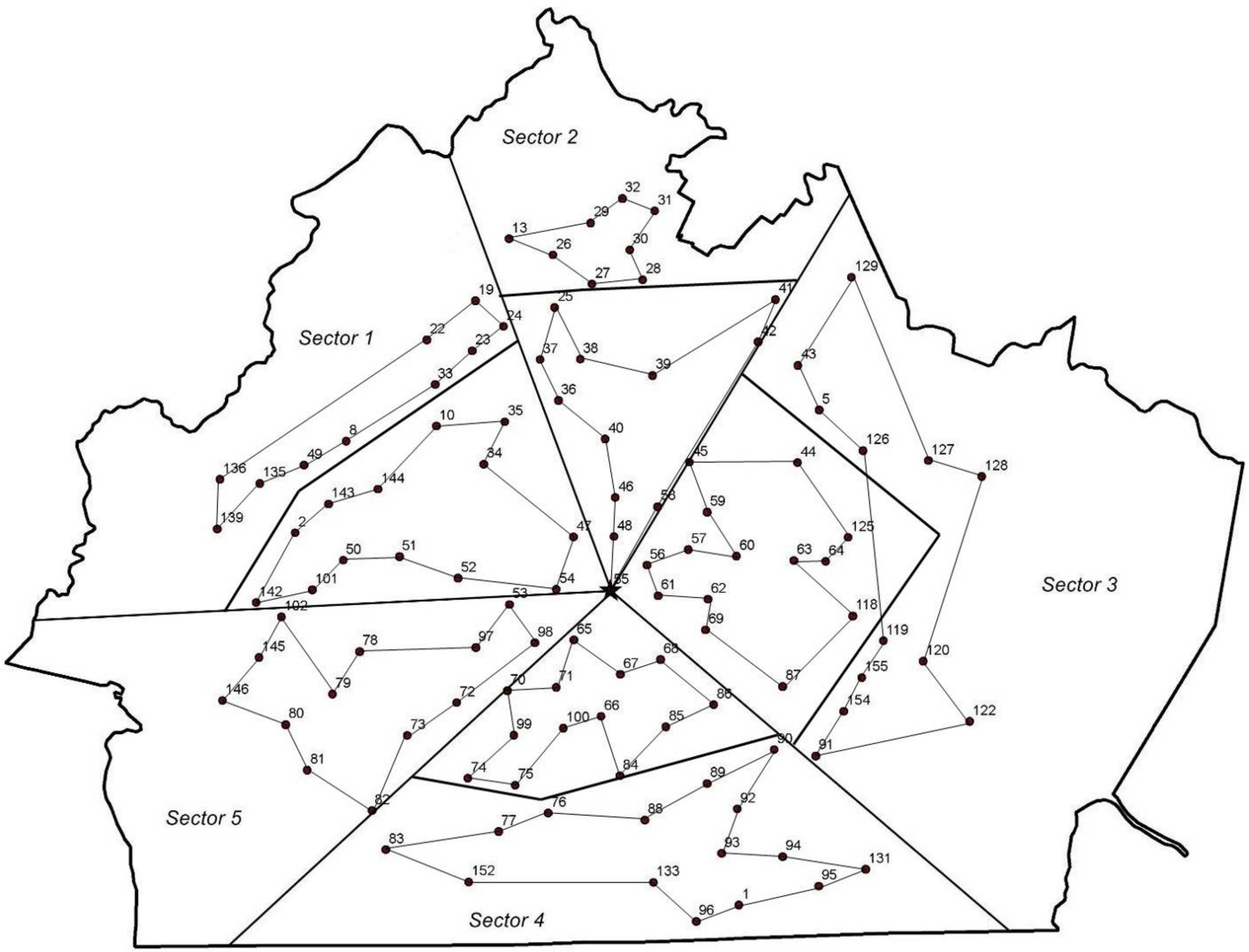


**Figure 6.44 Five sectors and nine sub sectors defined for Policy 5 with optimal Hamiltonian cycles for each loader.**

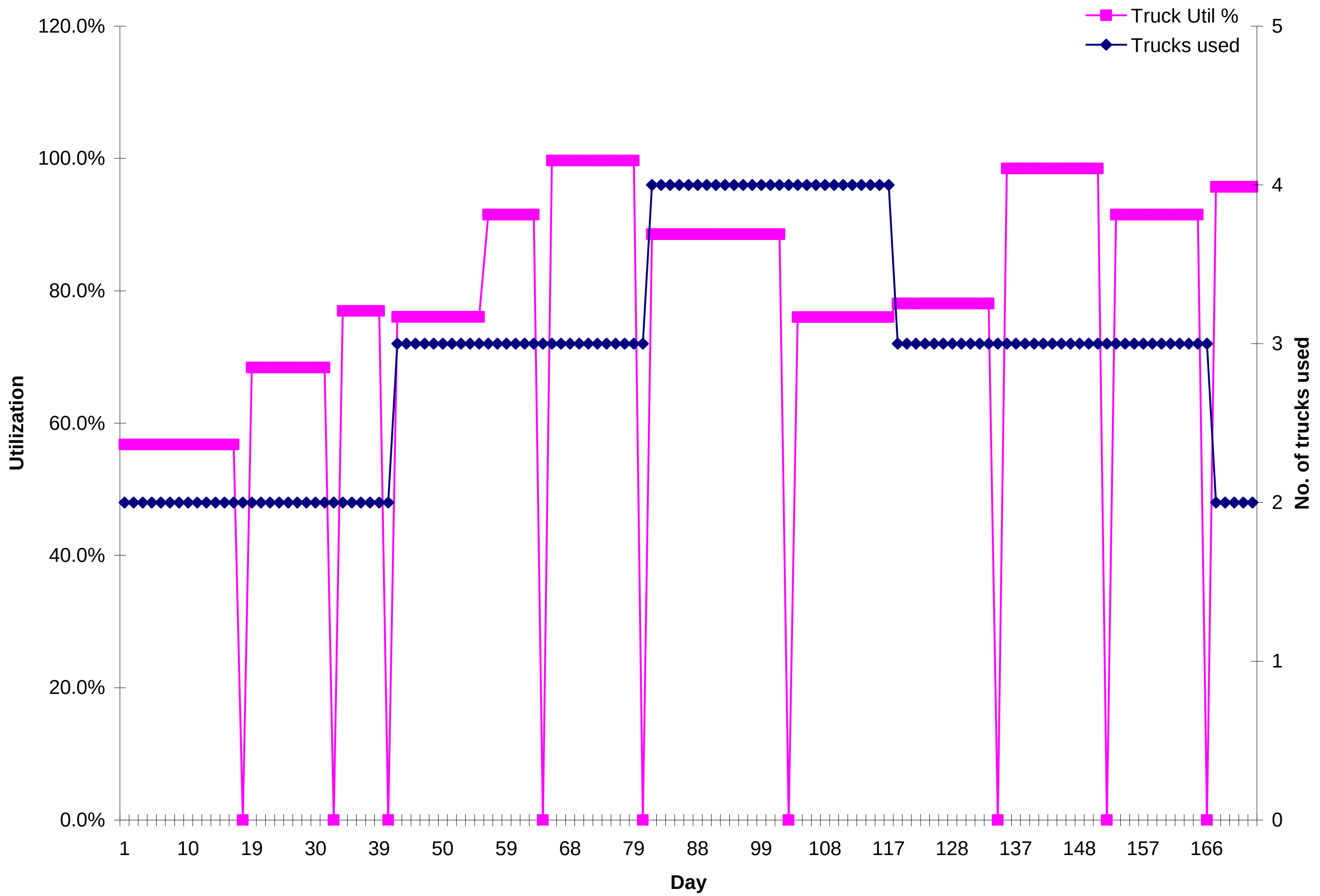


**Figure 6.45 Truck utilization and number of trucks used by Loader 3, Policy 5, 50% land use rate**

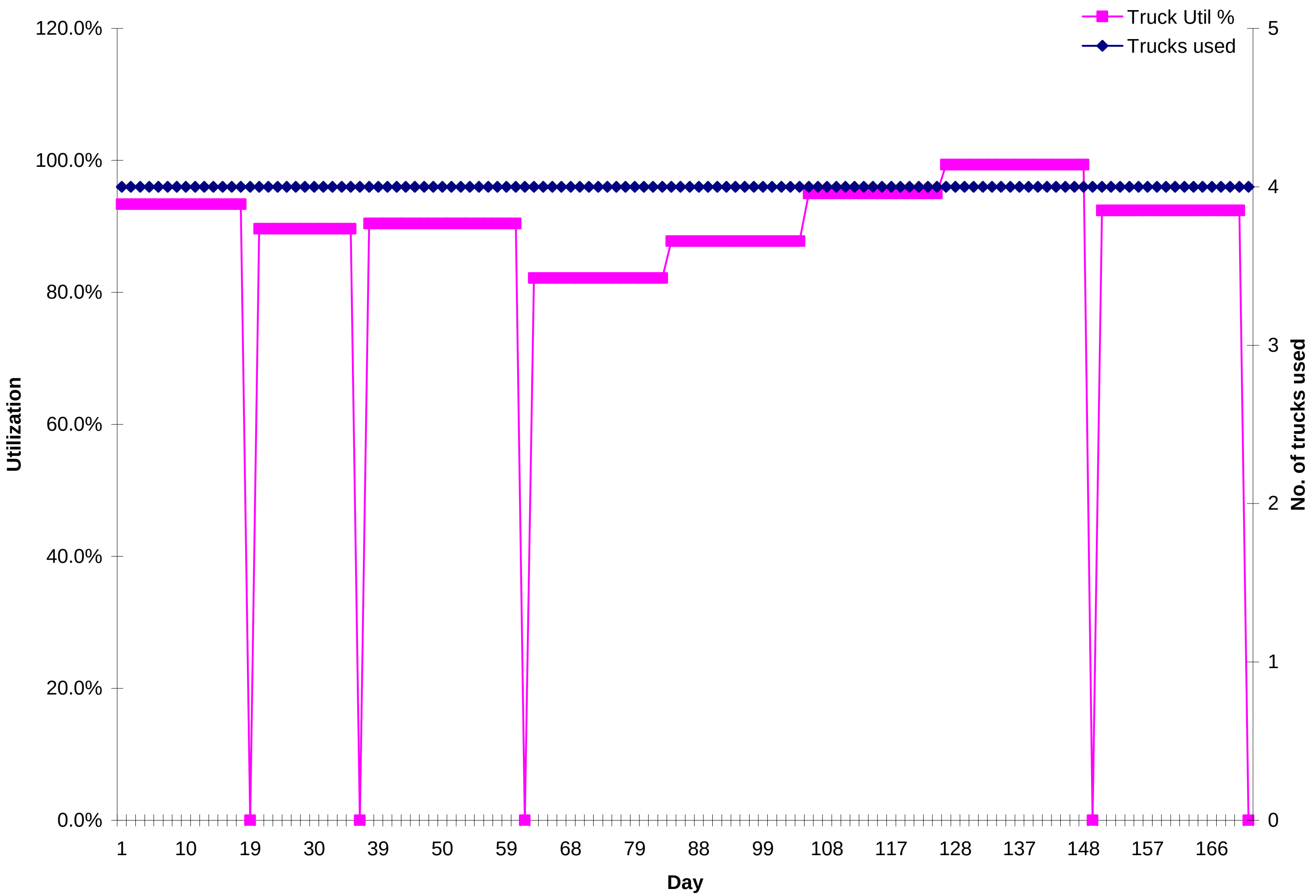


**Figure 6.46 Truck utilization and number of trucks used by Loader 4, Policy 5, 50% land use rate**

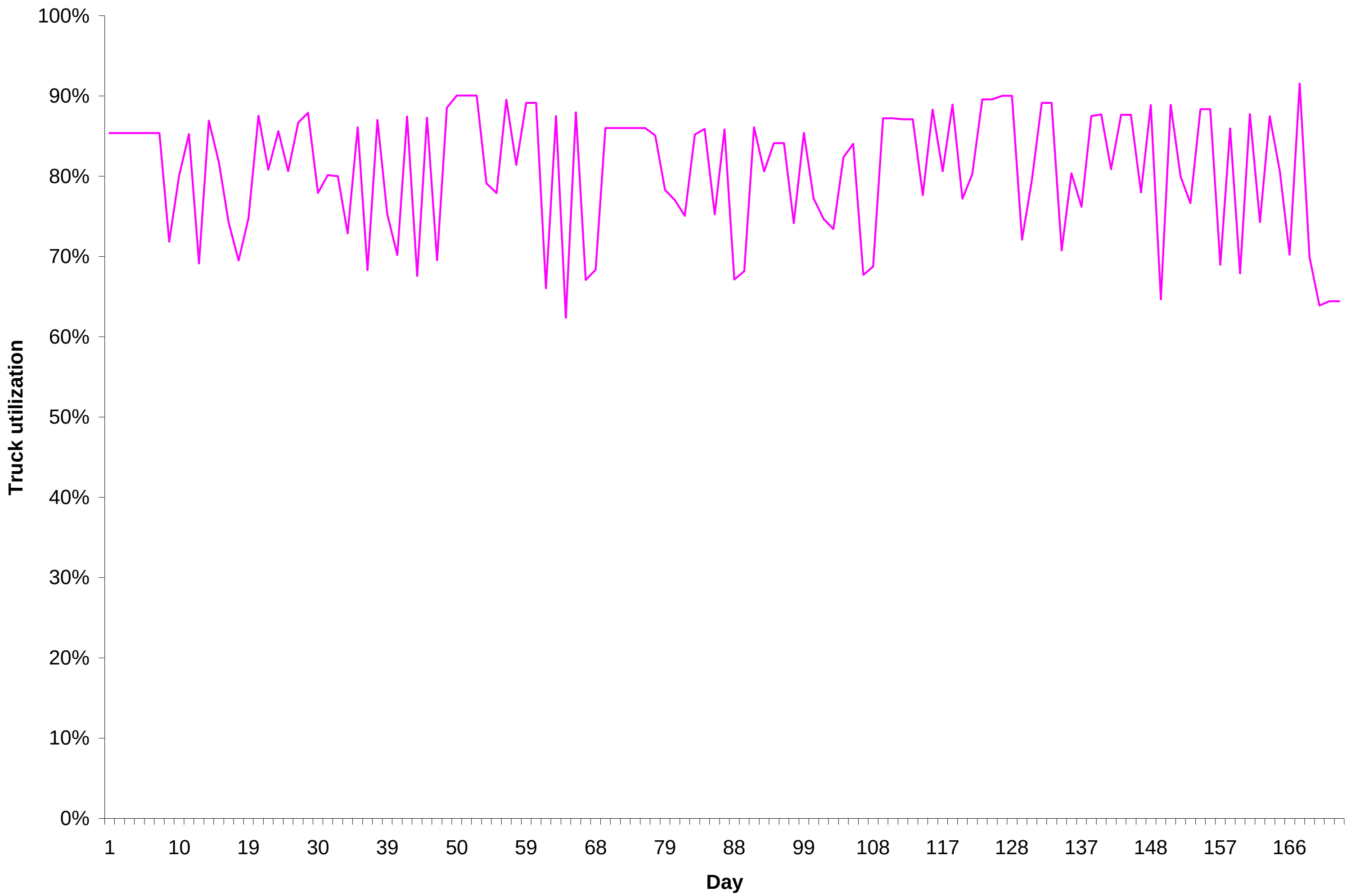


**Figure 6.47 Truck utilization, Policy 5, 50% land use rate**

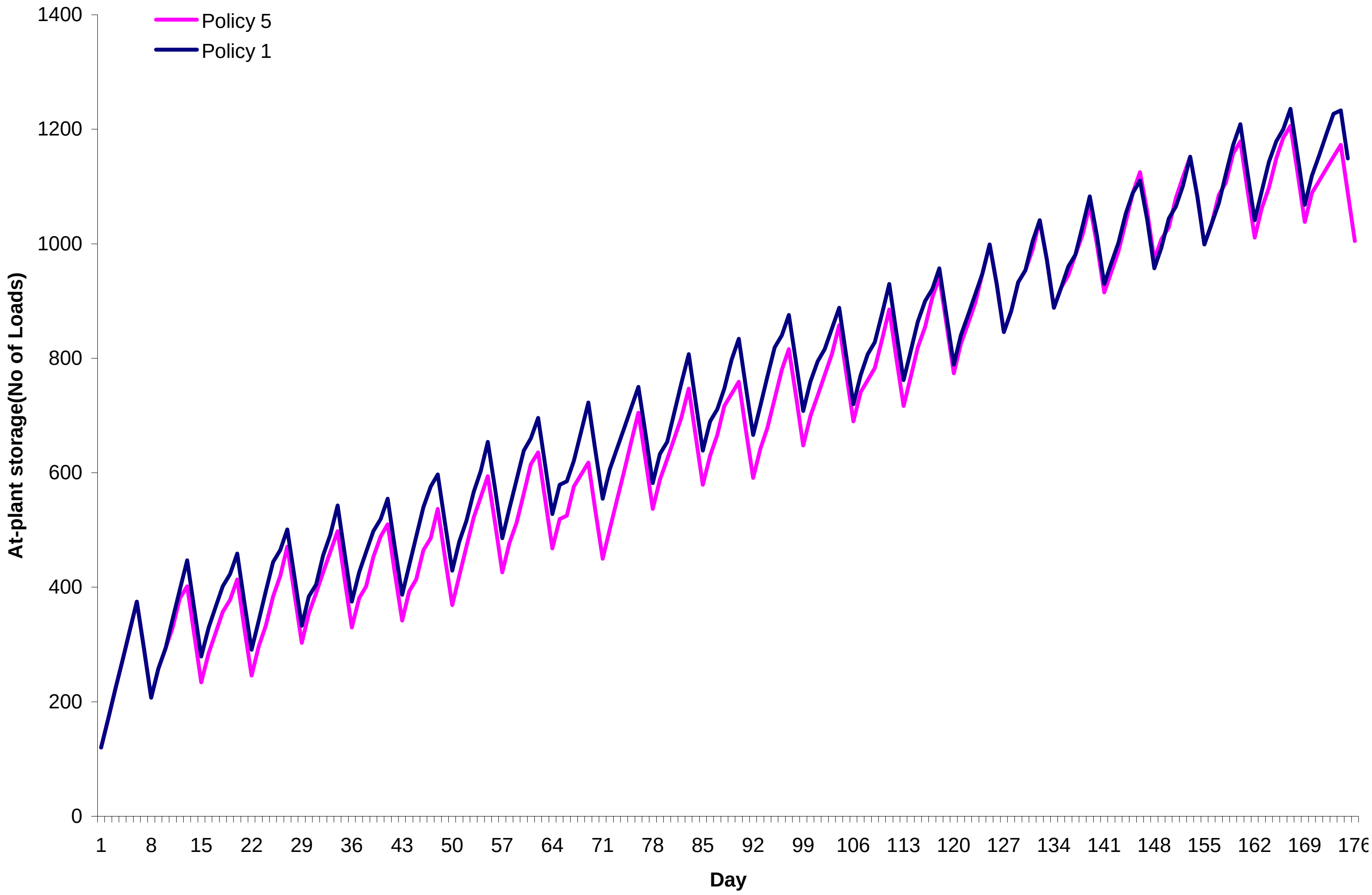


**Figure 6.48 At-plant storage in Policy 1 and 5, 50% land use rate**

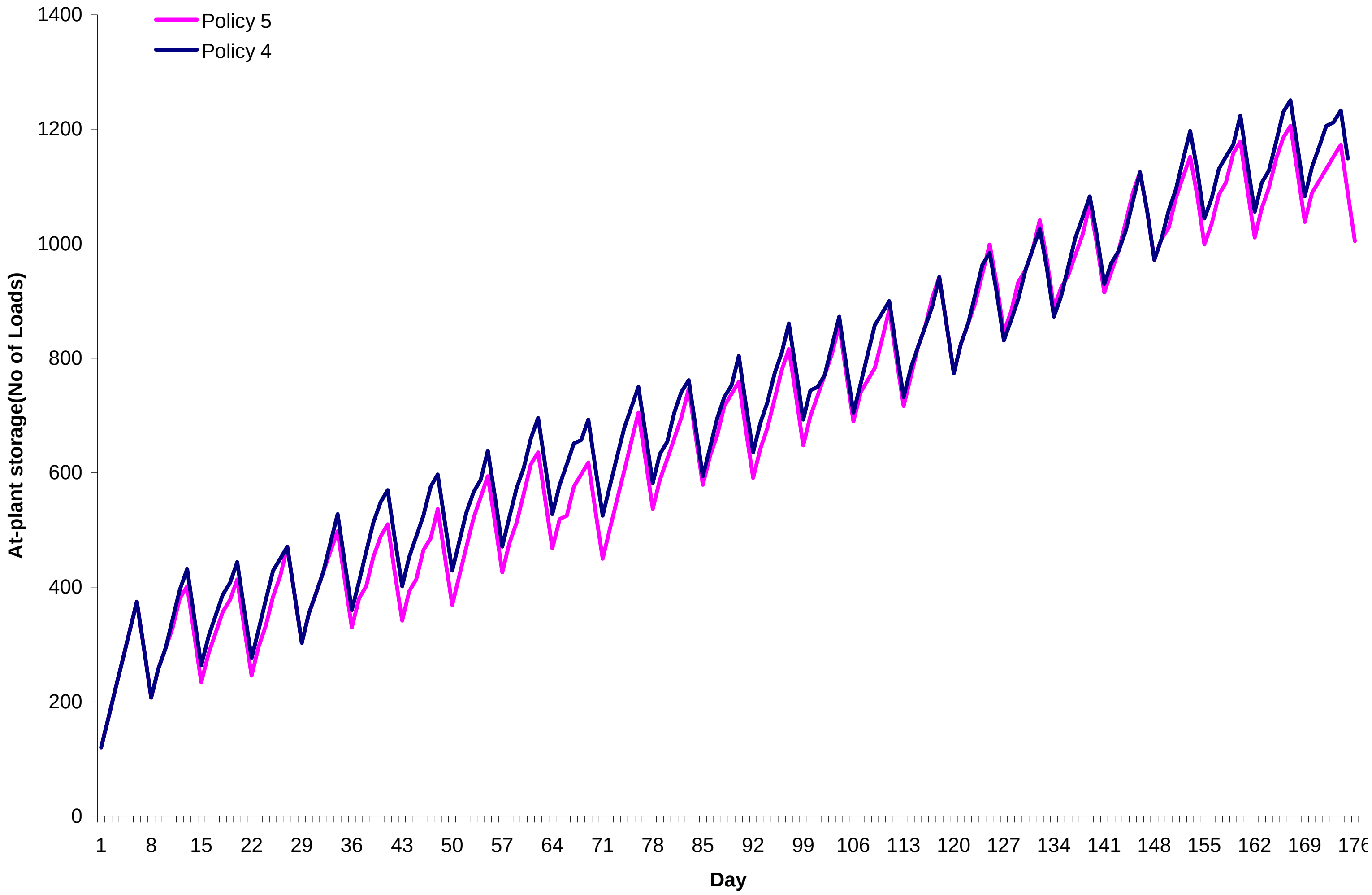


**Figure 6.49 At-plant storage in Policy 4 and 5, 50% land use rate**

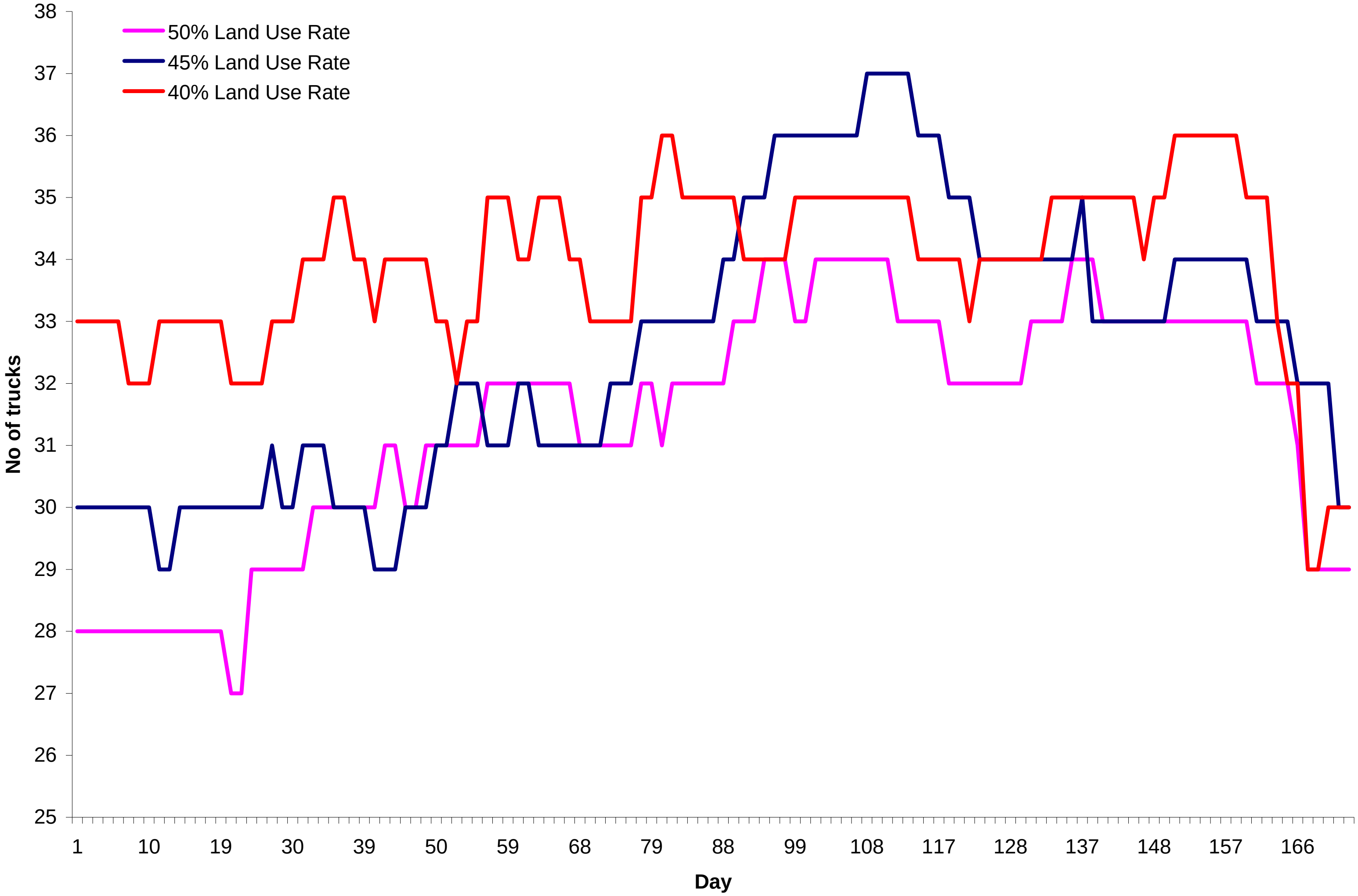


**Figure 6.50 Total truck usage with nine loaders in Policy 5 as impacted by land use rates**

### *6.7 Policy 6 –Shortest Travel Time first and Longest Travel Time next, Part-time Loader and minimum loader travel (STT-LTT-C-HL-MLT)*

Policy 3 used a part-time loader to reduce inventory buildup at the plant, but suffered from high inter-SSL travel by loaders due to crisscrossing. Policy 4, on the other hand, has low inter-SSL travel distances due to optimal Hamiltonian cycles, but the plant inventory builds up to unacceptable levels due to Loader 9 operating at full capacity. Policy 6 combines part-time loader concept from Policy 3 and optimal Hamiltonian cycles from Policy 4, and was designed to address the individual drawbacks of Policies 3 and 4.

Figure 6.51 shows the variation in at-plant inventory level between Policies 1 and 6 as the season progresses. The inventory level varied from a maximum of 459, 402 and 435 to a minimum level of 120, 60 and 30 for land use rates of 50, 45 and 40% respectively. Figure 6.52 shows the number of trucks used by Policy 6 as the season progresses. The maximum numbers of trucks used by Policy 6 were 32, 33 and 34 for land use rates of 50, 45 and 40% respectively. The minimum numbers of trucks used were 26, 26 and 28 for land use rates of 50, 45 and 40%, respectively.

The average truck utilization rates did not show much variation between the three land use rates and was at 81%, 80%, and 79% for 50%, 45%, and 40% land use rates respectively. The overall truck utilization rates were similar than policies 1 to 6.

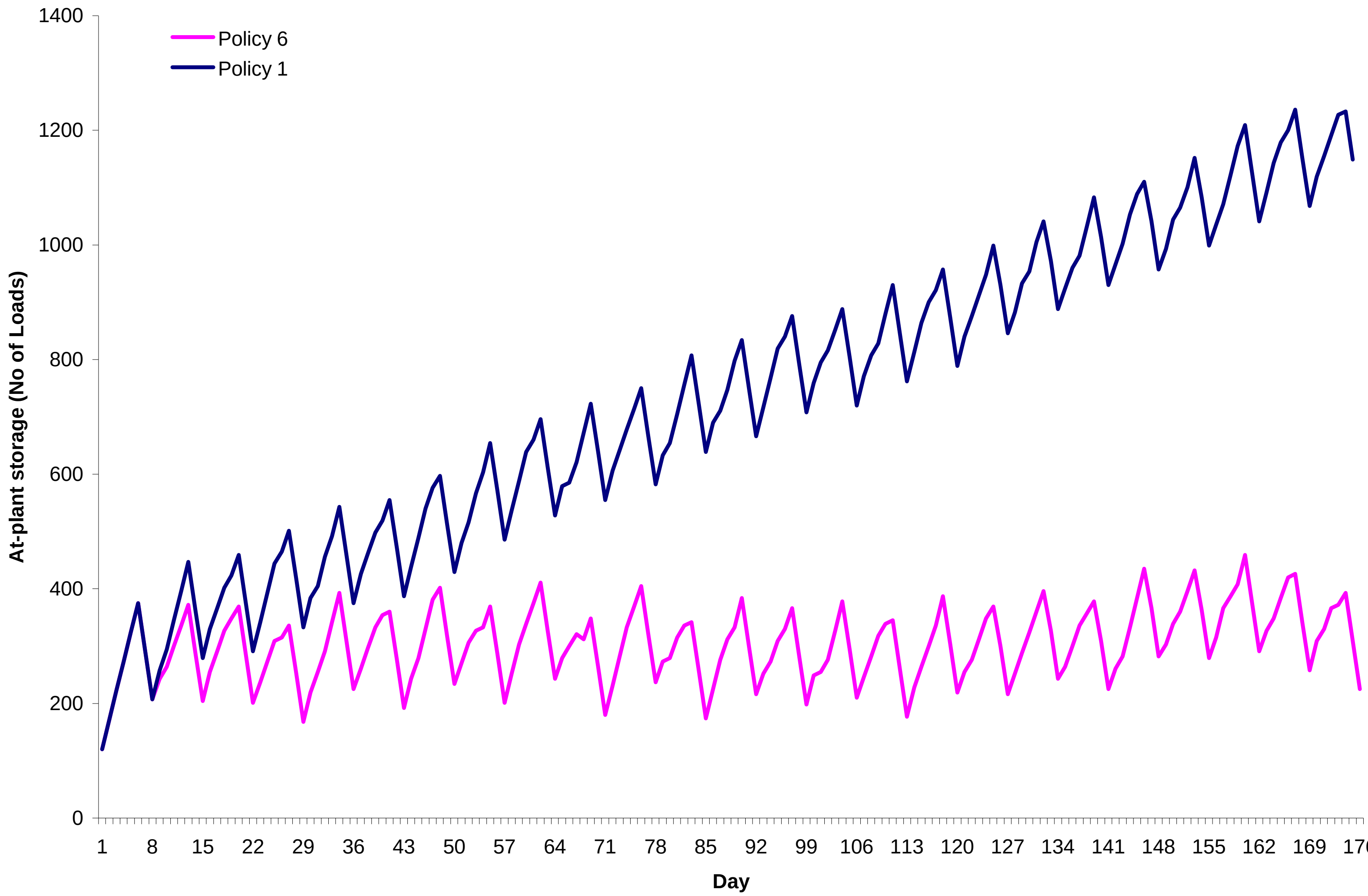


**Figure 6.51 At-plant inventory level for Policies 1 and 6, 50% land use rate**

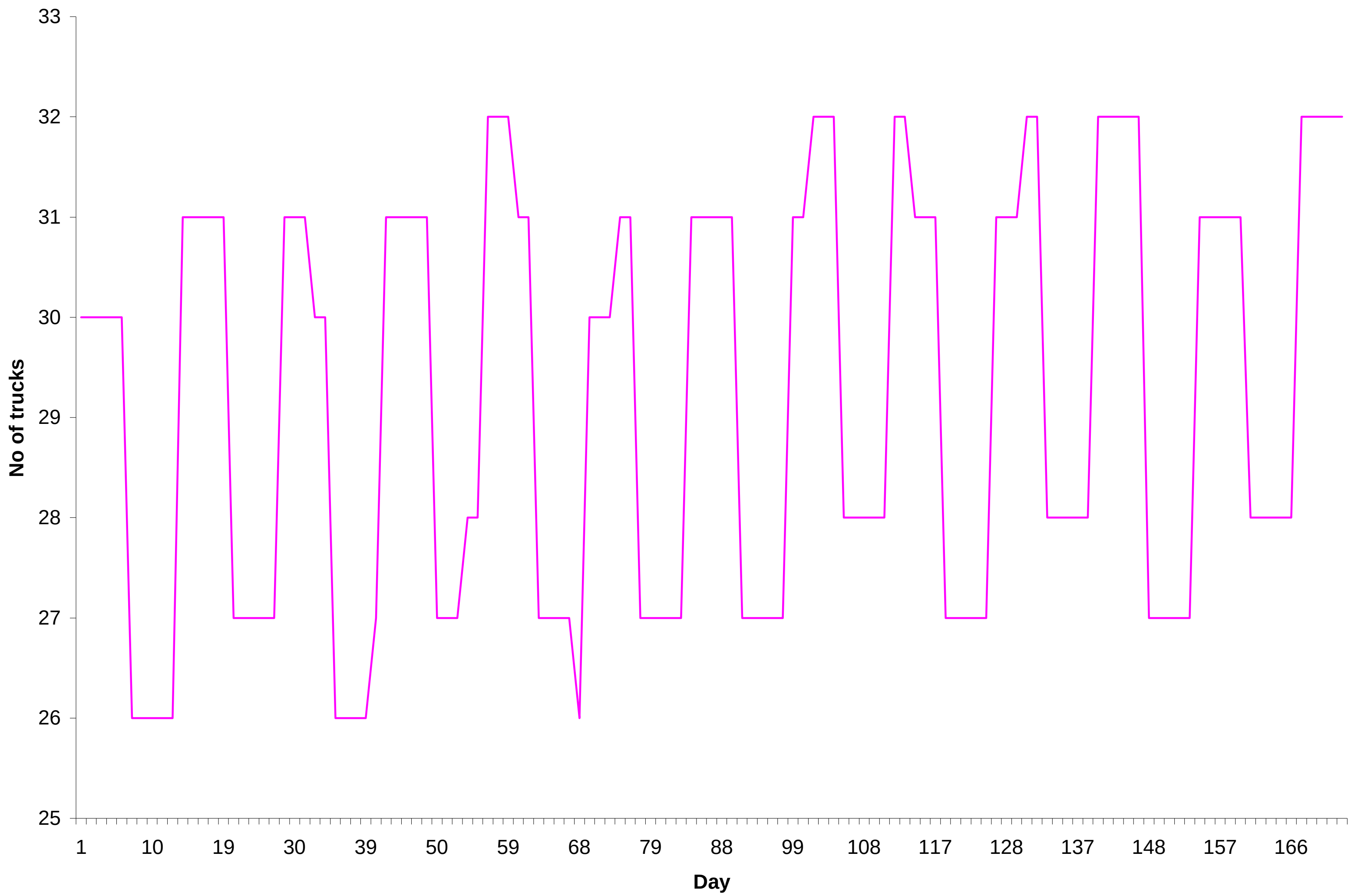


**Figure 6.52 No. of Trucks used for Policy 6, 50% land use rate**

## *6.8 Policy 7 – Sector Based Loader Assignment, with Part-time Loader*

Policy 3 which used a part-time loader to reduce inventory buildup at the plant suffered from high inter-SSL travel by loaders due to crisscrossing. Policy 5, on the other hand, had low inter-SSL travel distances due to a sector based optimal Hamiltonian cycles, but the plant inventory increased to unacceptable levels due to Loader 9 operating at full capacity. Policy 7 combined the half loader concept from Policy 3 and sector based optimal Hamiltonian cycles from Policy 5.

Figure 6.53 shows the number of trucks used by each loader in Policy 5, 50% land use rate. The truck demand for Loader 9 at the start of the season is 4, dropping to 3 and then to 2 before it starts rising and reaches a maximum of 5 just before the season ends. Figure 6.53 clearly shows that Loader 9 was the only loader which used 5 trucks during the season. When deciding which loader to operate every other week, this outlier in terms of truck usage was selected as decreasing Loader 9 usage will have the maximum impact on the number of trucks used by the system. Loader 9 showed similar behavior in 45% and 40% land use rates. Although other loaders did have SSLs with 5 truck demand, Loader 9 continued to have the maximum number of days with 5 truck operations and therefore the same rule was used for these utilization factors too.

Figure 6.54 shows the at-plant inventory level with Policy 7 at 50% land use rate. Figure 6.55 shows the number of trucks used by Policy 7 under 50, 45 and 40% land use rate respectively.

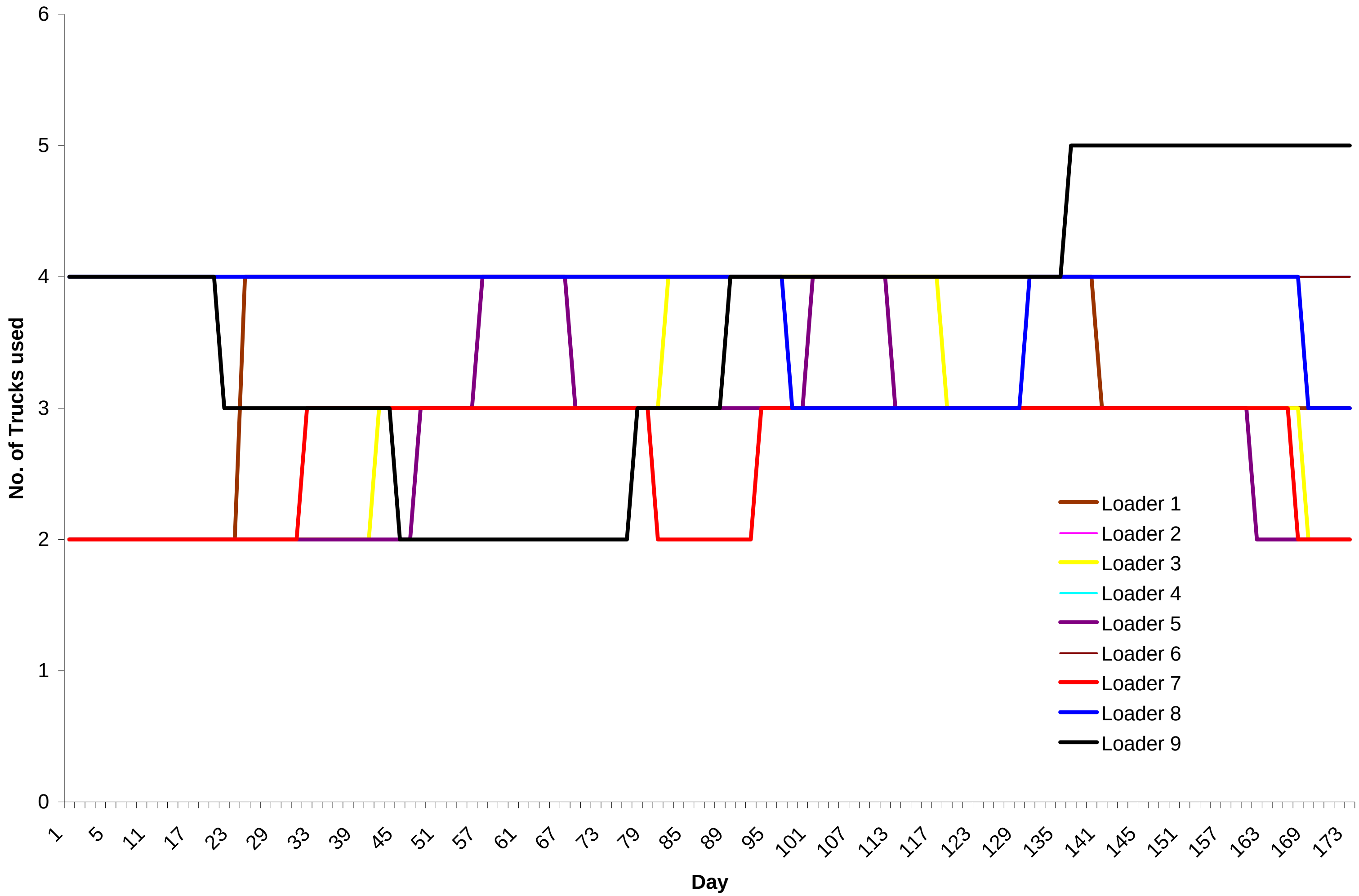


**Figure 6.53 Number of trucks used by each loader in Policy 5, 50% land use rate**

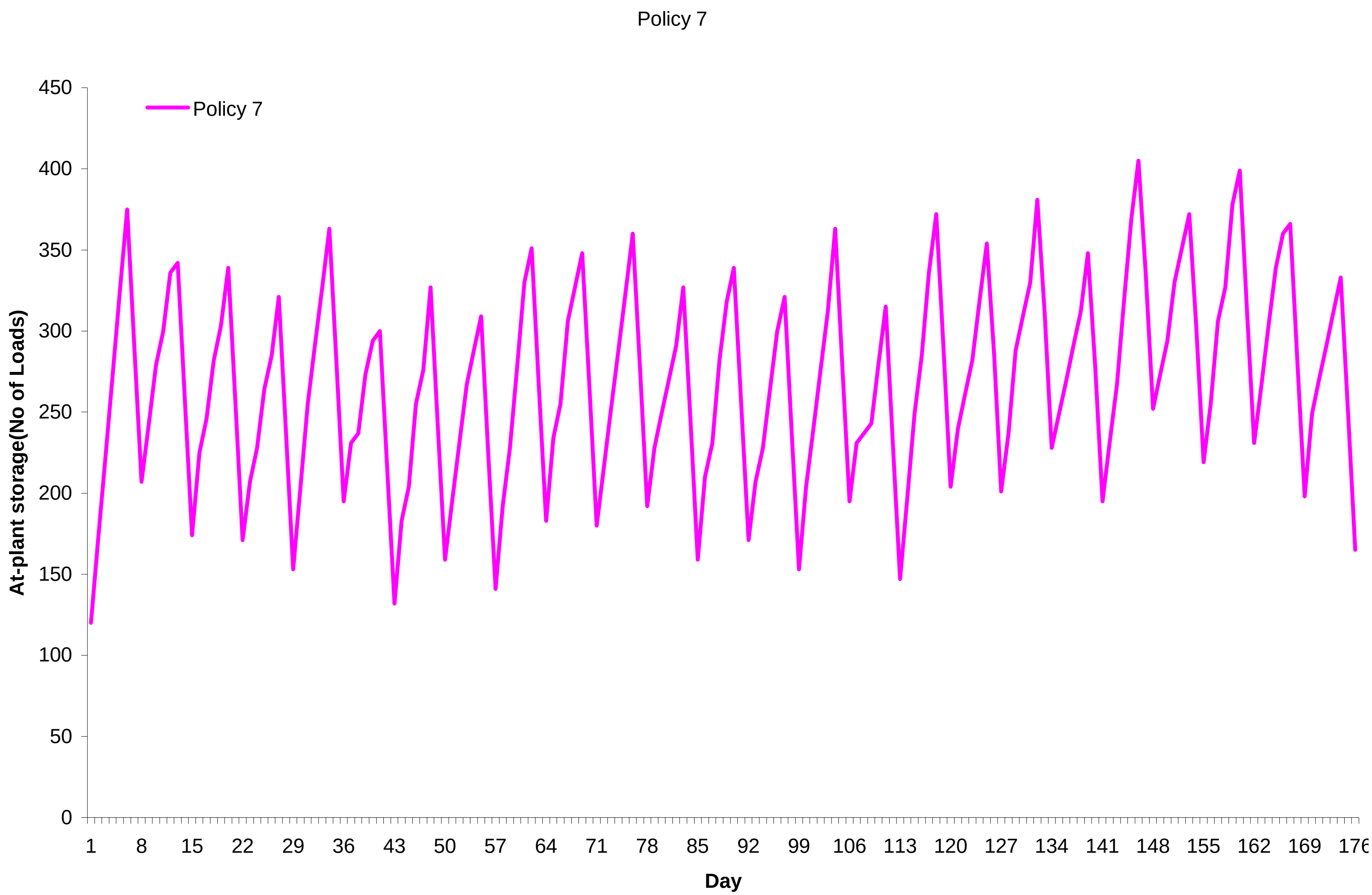


**Figure 6.54 At-plant inventory level for Policy 7, 50% land use rate**

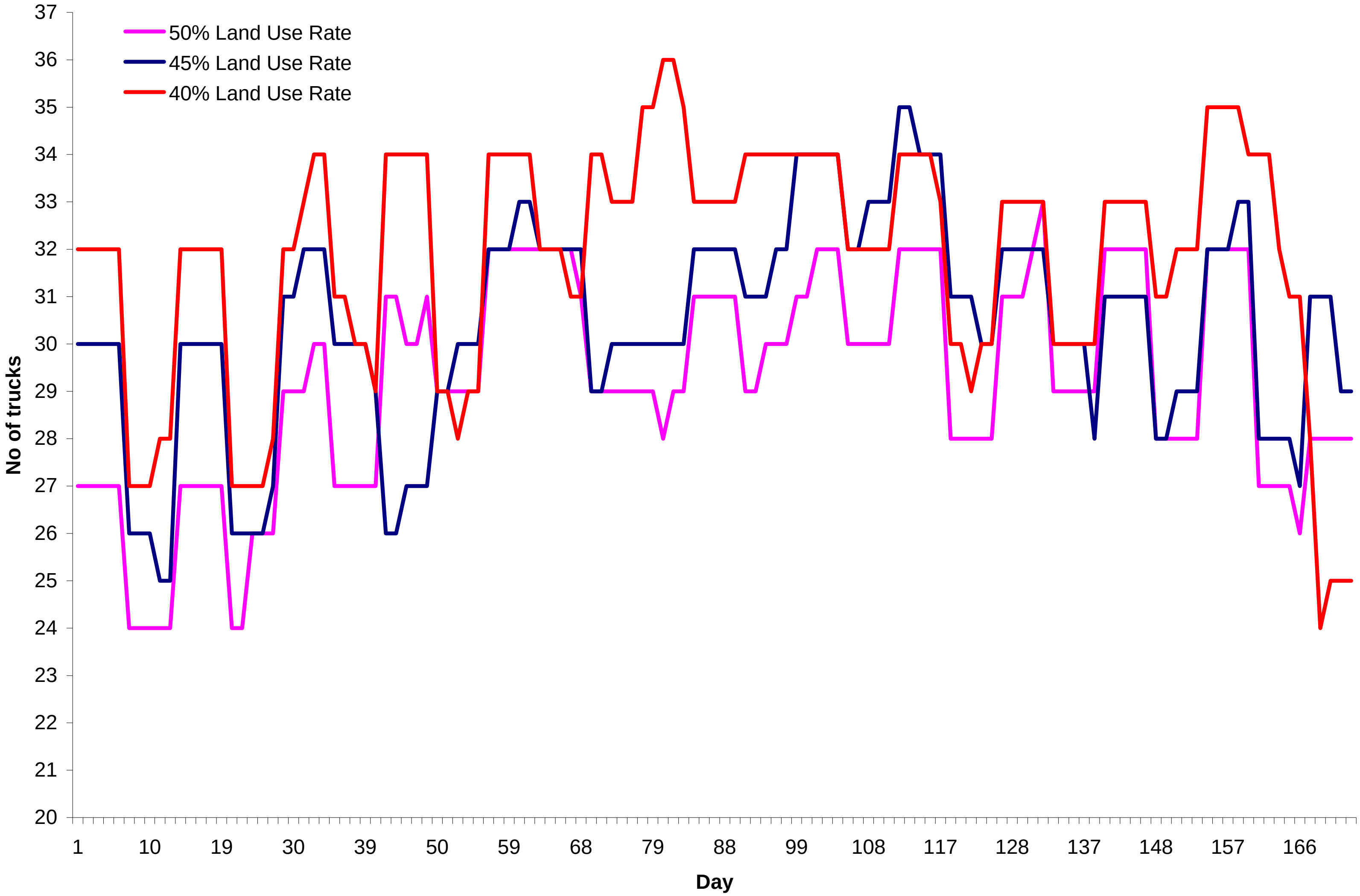


**Figure 6.55 No. of Trucks used for Policy 7 as impacted by land use rate**

## *6.9 Results:*

Table 6.1 shows the maximum number of trucks used, the average number of trucks used, truck utilization, maximum at-plant inventory, and the average at-plant inventory under Policies 1 to 7 with 50%, 45% and 40% land use rates. Policy 1 (STT-LTT-C), which used a STT-LTT loader assignment, produced a schedule which had a high at-plant inventory (1,236 loads) during the season and large crisscrossing by loaders (5,492 km, 6,396 km, and 10,198 km for 50%, 45%, and 40% land use rate, respectively). Policy 2 (STT-LTT-WC) produced a schedule that had high truck usage when compared to Policy 1 (32, 33 and 34 in Policy 1 for 50%, 45%, and 40% land use rate, respectively vs. 36 for Policy 2) while sharing the same drawbacks. The only advantage for Policy 2 was nearly equal travel distances for loaders in LTT or STT set. This advantage does not produce any significant drop in operational cost and therefore Policy 2 was dropped from further analysis.

Policy 3 (STT-LTT-C-HL) produced a schedule that reduced at-plant inventory level that never exceeded 4 days storage (480 loads). This low inventory level was preferred as a large at-plant inventory increases the storage cost and effectively increases the plant's raw material cost. But this policy still had crisscrossing loaders. Policy 4 (STT-LTT-MLT) used Policy 1 to produce a schedule that had no crisscrossing, but suffered from excess at-plant inventory as it used the same SSLs from Policy 1. So a new policy, Policy 6 (STT-LTT-MLT-HL) was formulated combining the part-time loader from Policy 3 and minimum loader travel constraint from Policy 4. Policies 3 and 4 were dropped from further analysis.

Under Policy 6, the at-plant inventory level stayed below 4 days and this policy was used for the next step in the process, namely, discrete event simulation, to validate its performance. Policy 5 (Sector Based Loader Assignment), which divided the entire procurement region into sectors, also suffered from the excess at-plant inventory level. The part-time loader concept from Policy 3 was combined with Policy 5 to produce

Policy 7 (Sector Based Loader Assignment with part-time Loader). Policy 5 was dropped from further analysis.

**Table 6.1 Summary table for Policies 1 to 7**

| Policy | Maximum Number of Trucks Used | Average Number of Trucks Used | Average Truck utilization (%) | Maximum Inventory Level at the Plant | Average Inventory Level at the Plant |
|---|---|---|---|---|---|
| Policy 1, 50% land use rate | 32 | 31 | 81 | 1236 | 732 |
| Policy 1, 45% land use rate | 33 | 33 | 80 | 1146 | 695 |
| Policy 1, 40% land use rate | 34 | 34 | 79 | 942 | 573 |
| Policy 2, 50% land use rate | 36 | 31 | 81 | 1173 | 666 |
| Policy 2, 45% land use rate | 36 | 32 | 80 | 1146 | 642 |
| Policy 2, 40% land use rate | 36 | 34 | 79 | 906 | 543 |
| Policy 3, 50% land use rate | 32 | 29 | 80 | 414 | 294 |
| Policy 3, 45% land use rate | 33 | 30 | 80 | 414 | 285 |
| Policy 3, 40% land use rate | 34 | 31 | 79 | 375 | 151 |
| Policy 4, 50% land use rate | 32 | 31 | 81 | 1251 | 723 |
| Policy 4, 45% land use rate | 33 | 33 | 80 | 1116 | 672 |
| Policy 4, 40% land use rate | 34 | 34 | 79 | 1101 | 662 |
| Policy 5, 50% land use rate | 34 | 31 | 81 | 1206 | 693 |
| Policy 5, 45% land use rate | 37 | 33 | 80 | 1206 | 689 |
| Policy 5, 40% land use rate | 36 | 34 | 79 | 1011 | 621 |
| Policy 6, 50% land use rate | 32 | 29 | 81 | 459 | 302 |
| Policy 6, 45% land use rate | 33 | 30 | 80 | 417 | 282 |
| Policy 6, 40% land use rate | 34 | 31 | 79 | 435 | 274 |
| Policy 7, 50% land use rate | 33 | 29 | 81 | 405 | 268 |
| Policy 7, 45% land use rate | 35 | 30 | 80 | 420 | 271 |
| Policy 7, 40% land use rate | 36 | 32 | 79 | 375 | 249 |

The STT-LTT rule used to generate schedules consistently provided lower maximum trucks used in one season than comparable policies. The superiority of this strategy was due to the smooth transition of truck requirement from one SSL to the next in a loader's schedule. This smooth transition was missing in Policy 2 and caused a high variation in truck requirement as the season progressed. The rearrangement of SSLs within a loader's schedule as in Policy 4 did not remove this property. Sector based policies (Policy 5 and Policy 7) did not have a smooth transition and therefore showed a higher variation than STT-LLT based policies. Although the increase in maximum truck requirement was small, the high truck ownership cost is expected to increase the final delivered biomass cost significantly.

The schedules also established the total distance trucks travel, along with interSSL loader travel distances. The number of moves that a loader makes in a season was also determined. Policies 6 and 7 were based on improvements to earlier policies and had the lowest at-plant inventory levels without any increase in maximum truck requirement. This led to the selection of these two policies for the next step in this study.

Chapter 7 deals with the design and construction of a discrete event simulation model based on the plant's transportation system. It was used to validate that the Policies 6 and 7 are capable of supplying the required amount of loads to the plant. It differs from the analysis in this chapter as the inventory level in this chapter is aggregated on a daily basis and therefore if the plant runs out of inventory for a very short time period, this analysis will not be able to determine that occurrence.

# Chapter 7 – Discrete event Simulation and Economic analysis

## *7.1 Introduction:*

The previous chapter (Chapter 6: Strategies for Scheduling of Loaders and Trucks) dealt with formulating scheduling strategies for a biomass logistics system. When formulating schedules for unloading SSLs, the policies dealt with inventory level and the total number of trucks on a per day basis. That is, if the inventory level at the plant dropped to zero during several hours, the analysis, which looked at aggregated numbers on a per day basis, would not be able to see that event. A discrete event model, which simulates each and every load through the logistic system, would be able to identify such an occurrence.

The two best scheduling strategies (Policy 6 and Policy 7) from analysis in Chapter 6 were selected. Their corresponding schedules were generated and run through a discrete event simulation model, constructed based on the logistic system, and these runs were used to validate the performance of these strategies.

## *7.2 Model Setup:*

The model was coded using Arena® version 7.1 (Rockwell Software, 2002) and its built-in Visual Basic for Application (VBA) module. Arena allows the user to build a model using blocks with predefined functionality and this feature was used along with a custom VBA block to construct the system for simulation. The simulation model consists of three major components, namely an entity that flows through the simulation, a process module, and a resource set. In this model, a load flows through the entire process and therefore was modeled as an entity. Any operation that needs resources was modeled using a process model. Machines such as loaders and trucks with predefined capacity and availability were modeled as resources. These components are explained in detail in the following subsections.

### *7.2.1 Entities:*

Entities are objects that move through the system. In this particular simulation model, loads flow from the start of the simulation model to the end and were modeled as entities. Each entity (load) has attributes that can be set to allow for proper routing during the simulation run. In this simulation model, as each load goes through "Assign" block, the *Entity.Station* attribute is assigned based on the loader. Figure 7.1 shows the properties window for "Assign 1" block.

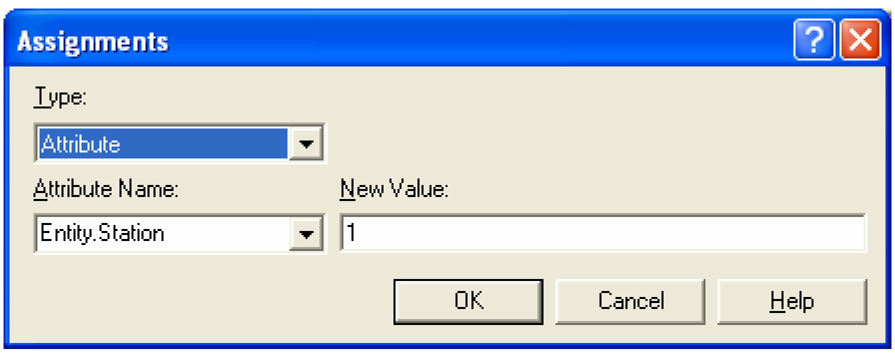


**Figure 7.1 Assignment properties**

### *7.2.2 Resources:*

Resources are elements of the system that are used by entities. They have a predefined capacity and a schedule that changes the resource states. When an entity uses a resource, the resource gets seized and will not be available to other entities. At the end of the process, the resource is released. If a resource is currently in use, a queue orders the entities so that they can be processed according to defined queuing rules (FIFO model was used for all queues in this simulation).

In this simulation model, there are four different types of resources, namely, Trucks, Loaders, Unloaders and Weigh machine. Other than Weigh machine, there are multiple copies of each resource. The simulation model uses nine loaders (named Loader1 to Loader 9), and three Unloaders (named Unloader1 to Unloader3). There are nine truck sets with each truck set's number varying on a daily basis. The actual number of trucks in each truck set is controlled by a VBA code block which assigns that value based on the policy schedule being simulated. Each of these resources can only serve one load at a time. Each resource has user defined operational parameters, normally, a schedule and scheduling rule. Figure 7.2 shows the properties for the Loader 1 resource.

The schedule rules are either calendar based or schedule based. For this simulation, all resources follow a schedule based policy. This policy allows the simulation resource states to change based on the simulation time. For example, the loader resource operates with a capacity of 1 for 12 hours during a day. For the next 12 hours, the loader has a capacity of 0. Figure 7.3 shows the schedule based policy, TruckSchedule, used by Loaders and Trucks. The Durations window allows the resource to change during the run. In this particular schedule, the resource varies from 0 to 1 every 12 hours.

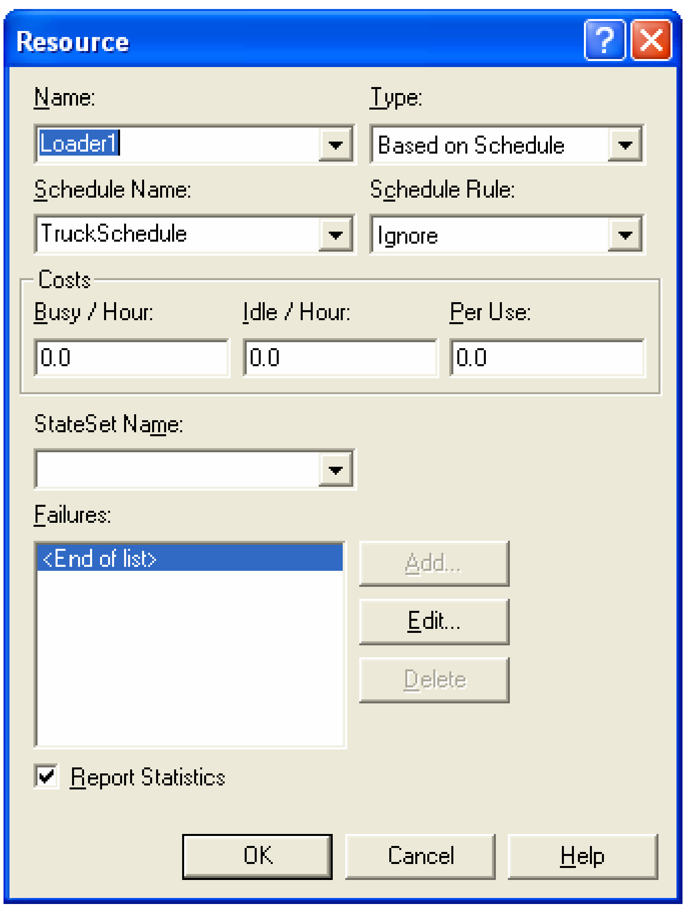


**Figure 7.2 Loader 1 resource properties**

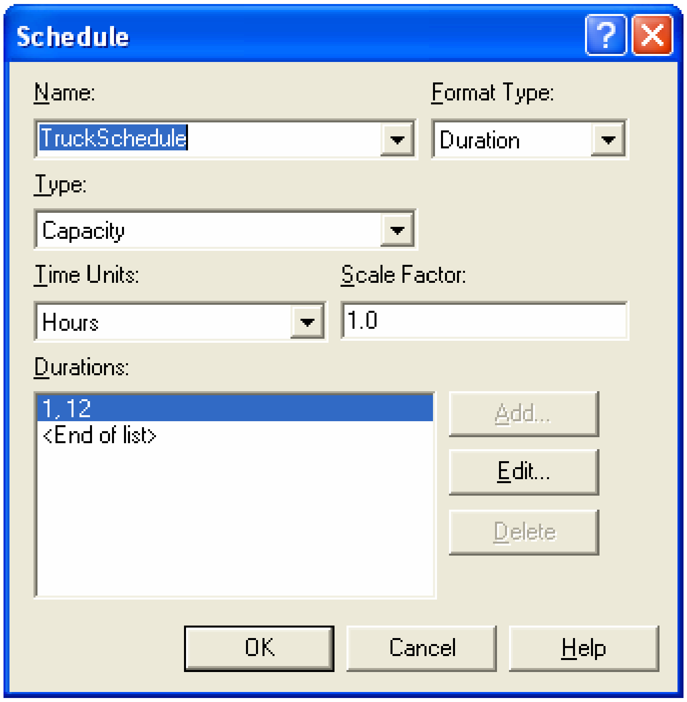


**Figure 7.3 Schedule properties**

### *7.2.3 Processes:*

This block is the main processing block in Arena. It provides an option for seizing and releasing resources and providing process delays. In this simulation model, there are three main processes at each SSL, namely, "Load Trucks with Loader", "Release Loader", and "Travel to Plant from Loader." Figure 7.4 shows the process properties for "Load Trucks with Loader 1" process. The other processes in the model occur at the plant and were "Weigh In", "Unload1", "Weigh out", "Plant" and "Travel to SSL." These processes along with their parameters are explained in the following sub-sections.

#### *7.2.3.1 Load Trucks with Loader:*

Each loader has a "Load Trucks with Loader" process. When an entity (load) arrives at the "Load Trucks with Loader" block, the process seizes one loader and one truck resource from Truck resource set assigned to that particular loader. Figure 7.4 shows the process properties for "Load Trucks with Loader1" block corresponding to Loader 1. The action dropdown list controls the type of process. In this block, the process uses Seize Delay action and uses two resources, Truck1 and Loader1. The process delay is controlled by Delay Type. A triangular distribution was used in this model with a minimum, mode and maximum values were defined by minLoadTime, LoadTime and maxLoadTime variables. These variables are assigned values during runtime by the VBA code (Figure 7.5). The minimum value was set as 30 min, the mode was set at 40 min and the maximum was set as 45 min.

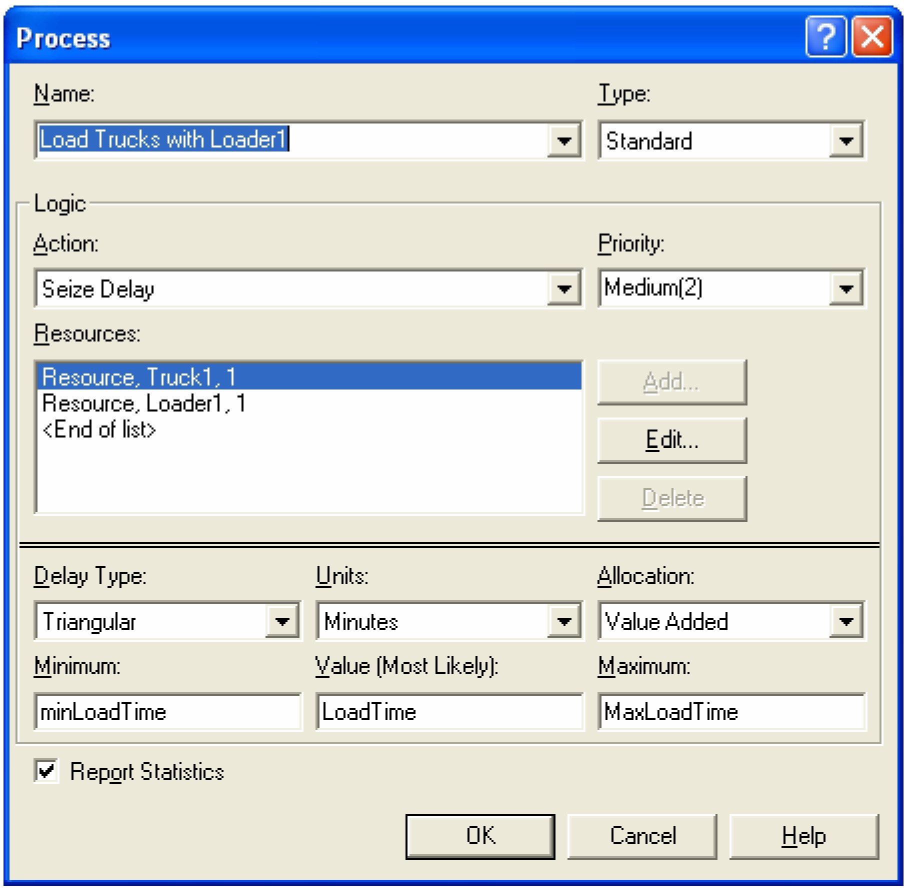


**Figure 7.4 Process properties**

```
'Code to set min, max and mode load times
s.VariableArrayValue(s.SymbolNumber("minloadTime")) = 30
s.VariableArrayValue(s.SymbolNumber("loadTime")) = 40
s.VariableArrayValue(s.SymbolNumber("maxloadTime")) = 45
```

**Figure 7.5 Code to set min, mode and max load times**

### *7.2.3.2 Release Loader:*

The loading operation uses two resources, a Truck and a Loader. If the “Load Trucks with Loader” process used a “Seize Delay Release” action, both the resources (Loader and Truck) would have been released at the end of the process. But the truck is assigned to the load till the load reaches the plant and is released only after the unloading operation. So a “Seize Delay” option was selected instead during “Load Trucks with Loader” process. A Release block which selectively releases resources on entities passing though it was used to release just the loader while keeping the truck assigned to the load after the loading process. Figure 7.6 shows the properties window for this process. One Loader1 resources was released for each entity which passed through it. The Loader 1 resource then becomes available for the next entity (load) in the process queue to use it.

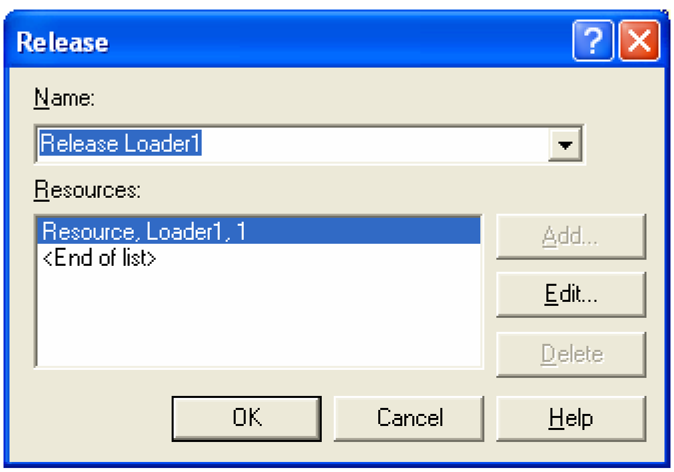


**Figure 7.6 Release loader properties**

### *7.2.3.3 Travel to Plant from Loader*

This process accounts for the time delay as the truck leaves the SSL and travels to the plant. As each load has a truck assigned to it, this block does not use any new resources. The process delays the flow of the entities by a constant or variable value depending on the delay type. The delay type can be a constant or one of many stochastic distributions which can be specified within Arena. When a load arrives at this block, it becomes unavailable for the duration of the delay. At the end of the delay time, it moves to the next block in the process. Figure 7.7 shows the property window for “Travel to Plant from Loader 1" block. Each load (entity) that moves through this block gets delayed by a constant time of L1Time. L1Time is changed by the VBA block at the beginning of each day depending on the policy being simulated.

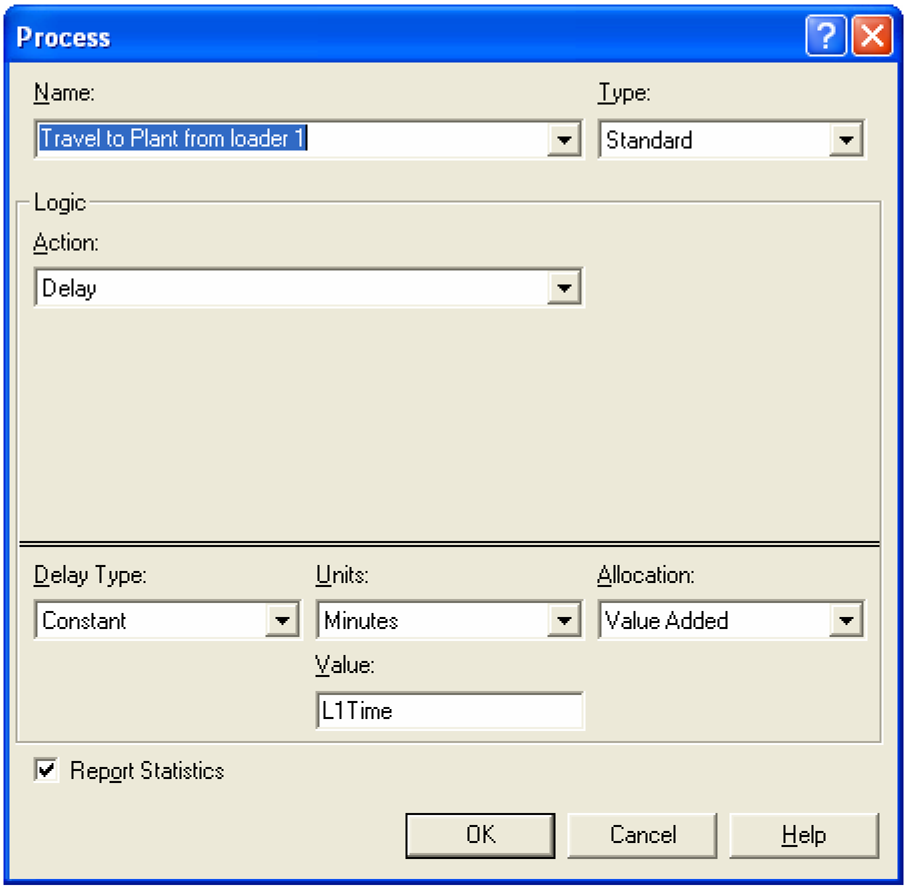


**Figure 7.7 Travel to Plant from Loader properties**

### *7.2.3.4 Weigh In*

All the trucks from all nine "Travel to Plant from Loader" blocks arrive at the "Weigh In" block. This block is a standard process block with "Seize, Delay, Release" action which uses one weigh machine resource. As each load arrives at the block, the process checks if the Weigh machine resource is available. If the weigh machine is free, then the load seizes the weigh machine and goes into a Delay phase. After the Delay phase is complete, the Weigh machine is released and the load (entity) moves to the next step in the process. If the weigh machine is not free, then the load enters a process queue where it waits till the resource becomes available to it. The queue follows a First In First Out (FIFO) policy and processes the loads in the same order in which they enter the queue. The delay time was modeled as a triangular distribution with the minimum, mode and maximum values given by minWeighTime, WeighTime and MaxWeighTime variables (Figure 7.8). These variables were set at the beginning of the simulation run by the VBA block (Figure 7.9). The minimum weigh time was set at 0.5 min, the mode was set as 1 min and the maximum was set as 1.5 min. These values were based on the field observation at a truck weigh station located in a wood fired electricity generating plant located in Hurt, Virginia. This plant receives and weighs about 150 trucks during a typical workday.

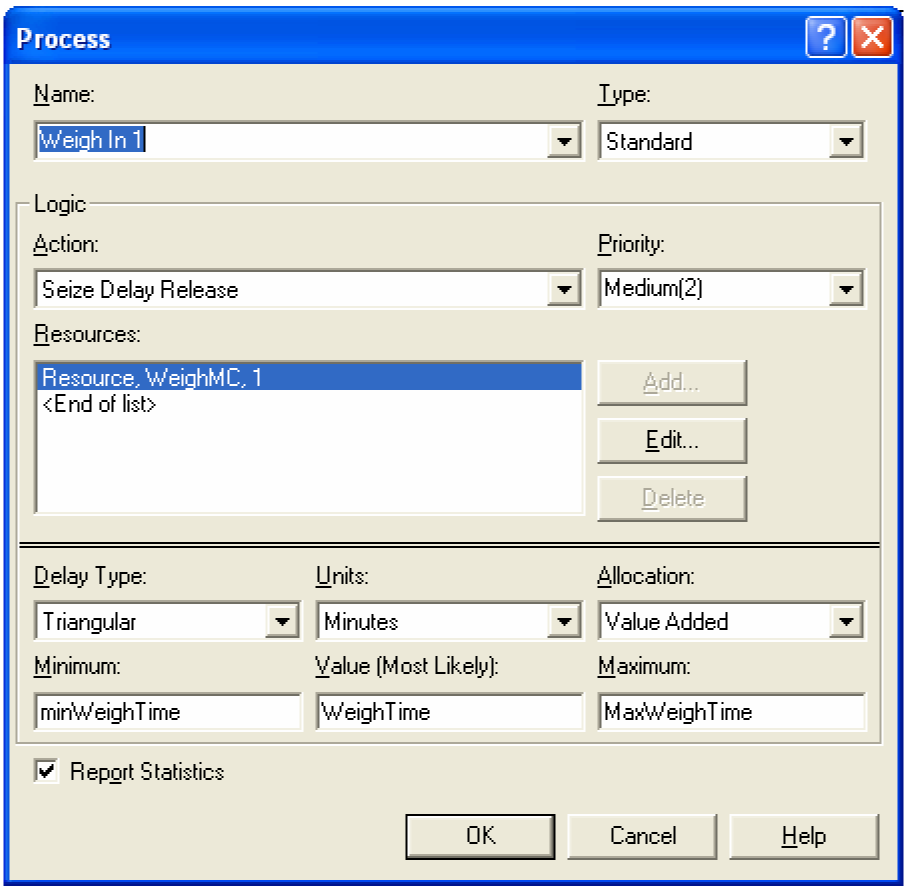


**Figure 7.8 Weigh In process properties**

```
'Code to set min, max and mode weigh time
s.VariableArrayValue(s.SymbolNumber("minWeighTime")) = 0.5
s.VariableArrayValue(s.SymbolNumber("WeighTime")) = 1
s.VariableArrayValue(s.SymbolNumber("maxWeighTime")) = 1.5
```

**Figure 7.9 VBA code to set min, mode and max weigh times**

### *7.2.3.5 Unload1*

Unload1 block is a standard process block with "Seize Delay and Release" action (Figure 7.10) used to model the unload operations at the plant. This process uses one resource from the Unloader set. The unloader set contains three unloaders, Unloader1, UnLoader 2 and UnLoader 3. Each of these machines in this set has an order of preferences, with Unloader1 having the highest and Unloader3 having the lowest preference. This process was modeled as a triangular distribution with the minimum, mode, and maximum values provided by minUnloadTime, UnloadTime, and maxUnloadTime variables. These variables were initialized by the VBA code at the beginning of each simulation run. Figure 7.11 shows the code for setting these times. The minimum unload time was set at 5 min, while the mode and the max were set as 10 min and 15 min, respectively.

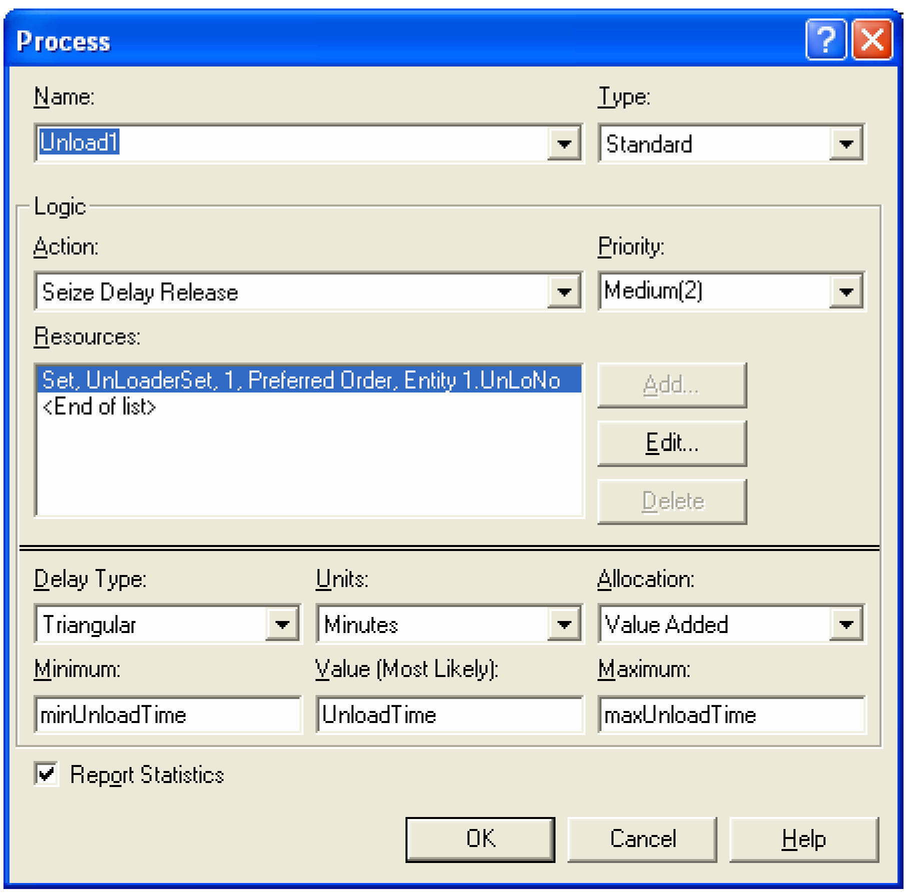


**Figure 7.10 Unload process properties**

```
'Code to set min, max and mode unload times
s.VariableArrayValue(s.SymbolNumber("minUnloadTime")) = 5
s.VariableArrayValue(s.SymbolNumber("UnloadTime")) = 10
s.VariableArrayValue(s.SymbolNumber("maxUnloadTime")) = 15
```

**Figure 7.11 VBA code for min, mode and max unload times**

### *7.2.3.6 Weigh Out*

The "Weigh out" process is similar to the Weigh in process except that it is used by the trucks before they are returned to their SSLs. It uses the same weigh machine resource with "Seize Delay and Release" action and has the same parameters as Weigh In block. This process is used to capture the empty weight of the truck. The difference between this weight and the weigh in weight will give total weight of the delivered biomass.

### *7.2.3.7 Plant*

The plant block was used to model the plant process which uses loads from the inventory. The block is a process block with "Seize Delay and Release" action which uses one plant machine resource. As soon as a load is unloaded at the plant, the load checks to see if the plant machine is available. If the plant machine is free then the load captures it and begins its process delay. If the plant is busy, the load then moves to the at-plant storage which is modeled as a FIFO queue by the Plant block. The number of loads waiting is tracked by the *Plant.queue* attribute.

The minimum, mode, and maximum processing times are controlled by minProcessTime, ProcessTime, and maxProcessTime variables (Figure 7.12). These values were initialized by VBA at the beginning of the simulation run (Figure 7.13). The minimum processing time for each load was set as 16.14 min, while the mode and maximum were set at 17.14 and 18.14 min, respectively.

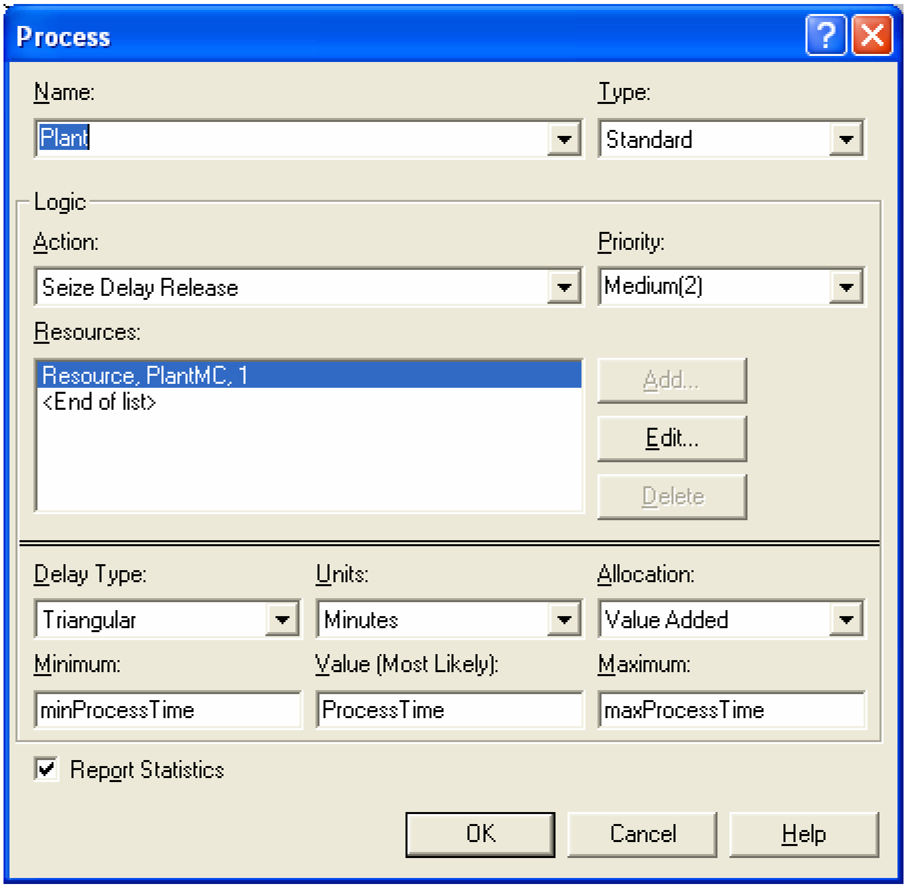


**Figure 7.12 Plant process properties**

```
'Code to set min, max and mode process times
s.VariableArrayValue(s.SymbolNumber("minProcessTime")) = 16.14
s.VariableArrayValue(s.SymbolNumber("ProcessTime")) = 17.14
s.VariableArrayValue(s.SymbolNumber("maxProcessTime")) = 18.14
```

**Figure 7.13 VBA code for min, mode and max plant processing times**

### *7.2.3.8 Travel to SSL*

After the load is delivered to the plant, the truck must return to the initial SSL for the next load. “Travel to SSL” block is used to model this process. Travel to SSL block is a process block with “Delay Release” action (Figure 7.14). An N-way conditional block, “Decide 1” was used to split the trucks leaving “Weigh Out 1” block and send each truck to the correct “Travel to SSL” blocks, Nos. 1 to 9, depending on *Entity.Station* attribute. Each “Travel to SSL” block has travel time equal to “Travel to Plant from Loader” block.

The delay in the process is controlled by variable L1Time which is initialized by the VBA block at the beginning of each day. At the end of the delay, the truck becomes available for the load (entity) at the SSL.

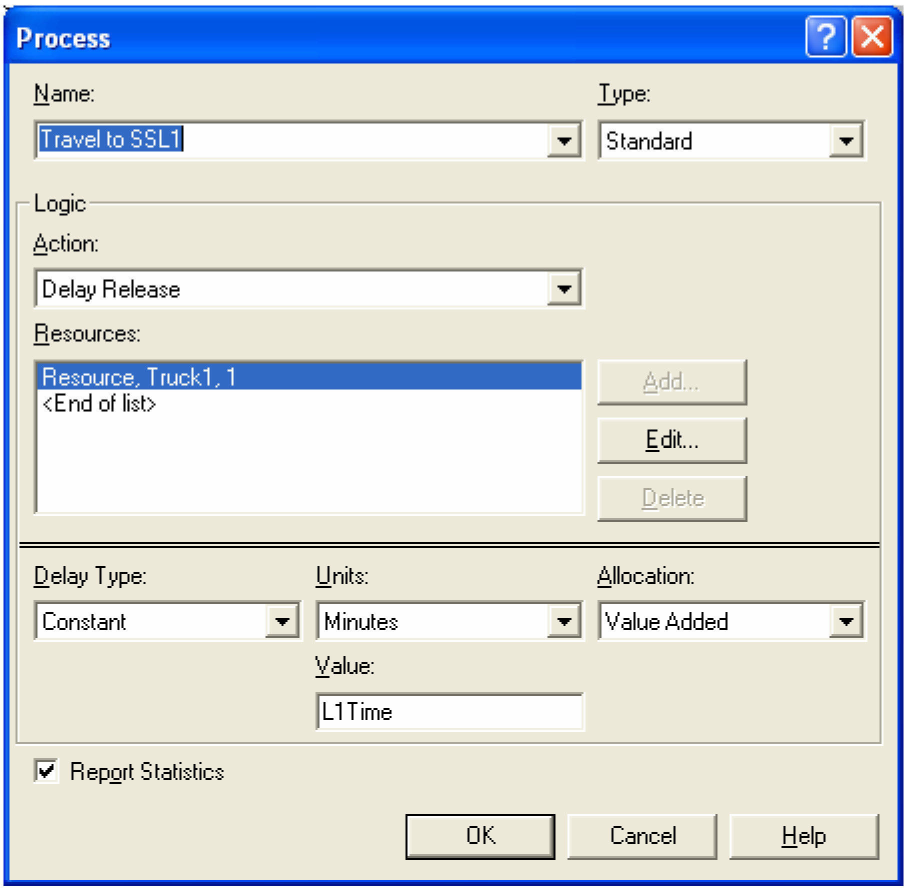


**Figure 7.14 Travel to SSL process properties**

## *7.3 Process Flow:*

Figure 7.15, Figure 7.16, and Figure 7.17 describe the process flow for the discrete event model. Figure 7.18 shows the Arena discrete event simulation model. The simulation model starts on Day 1, hour 0:00 with event "Create1" and runs for 4,200 hours, corresponding to 175 days (one season). The "Create 1" event occurs once every 24 hours and ends after 173 days, which is equal to the number of days the transportation system operates during a season. The last 2 days of the season (day 174 and 175) corresponds to a Saturday and a Sunday. The transportation system does not operate on those days, but the plant will continue to operate and this model accounts for that as the plant process simulation does not end until day 175.

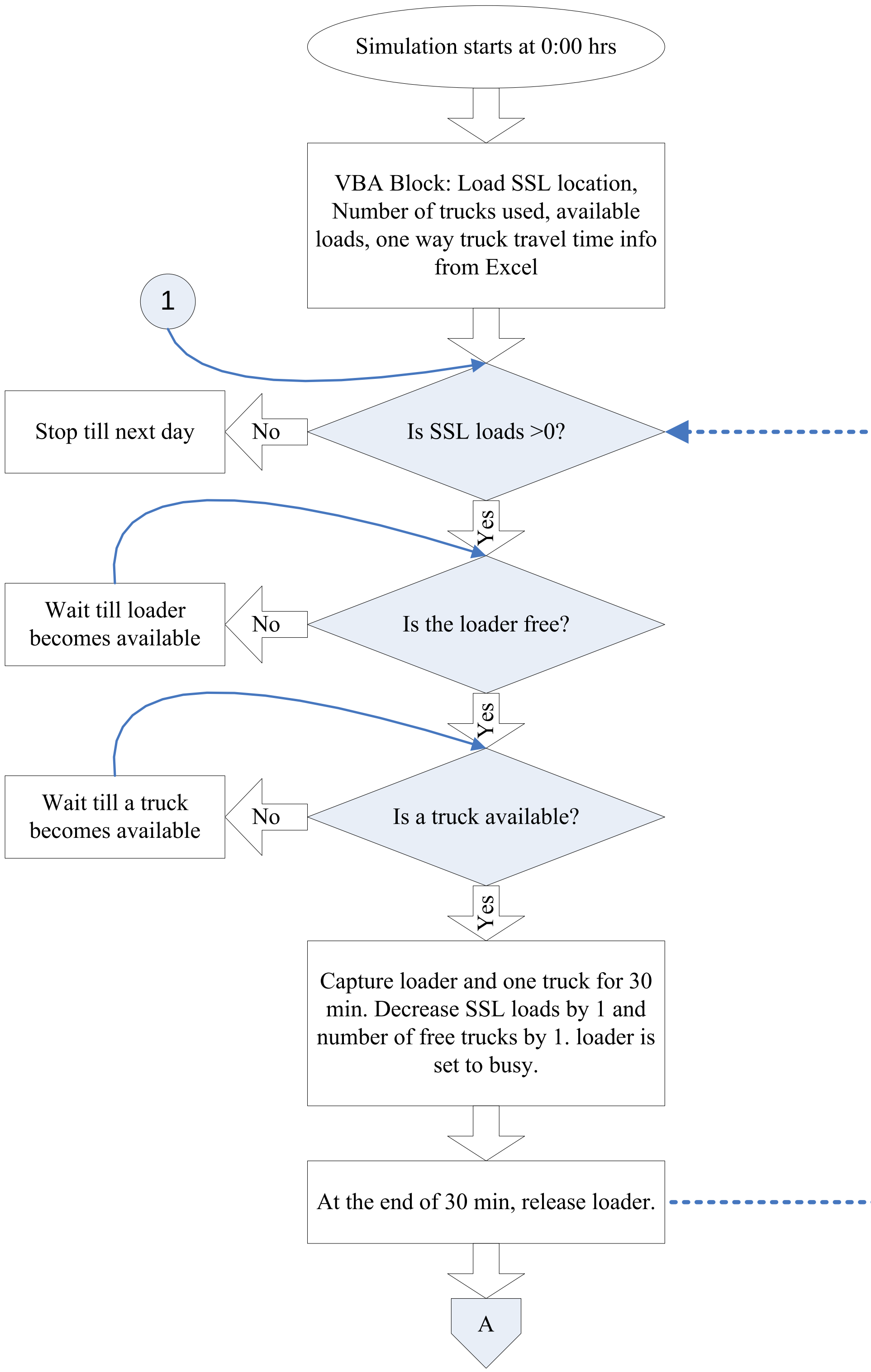


**Figure 7.15 Simulation Flowchart**

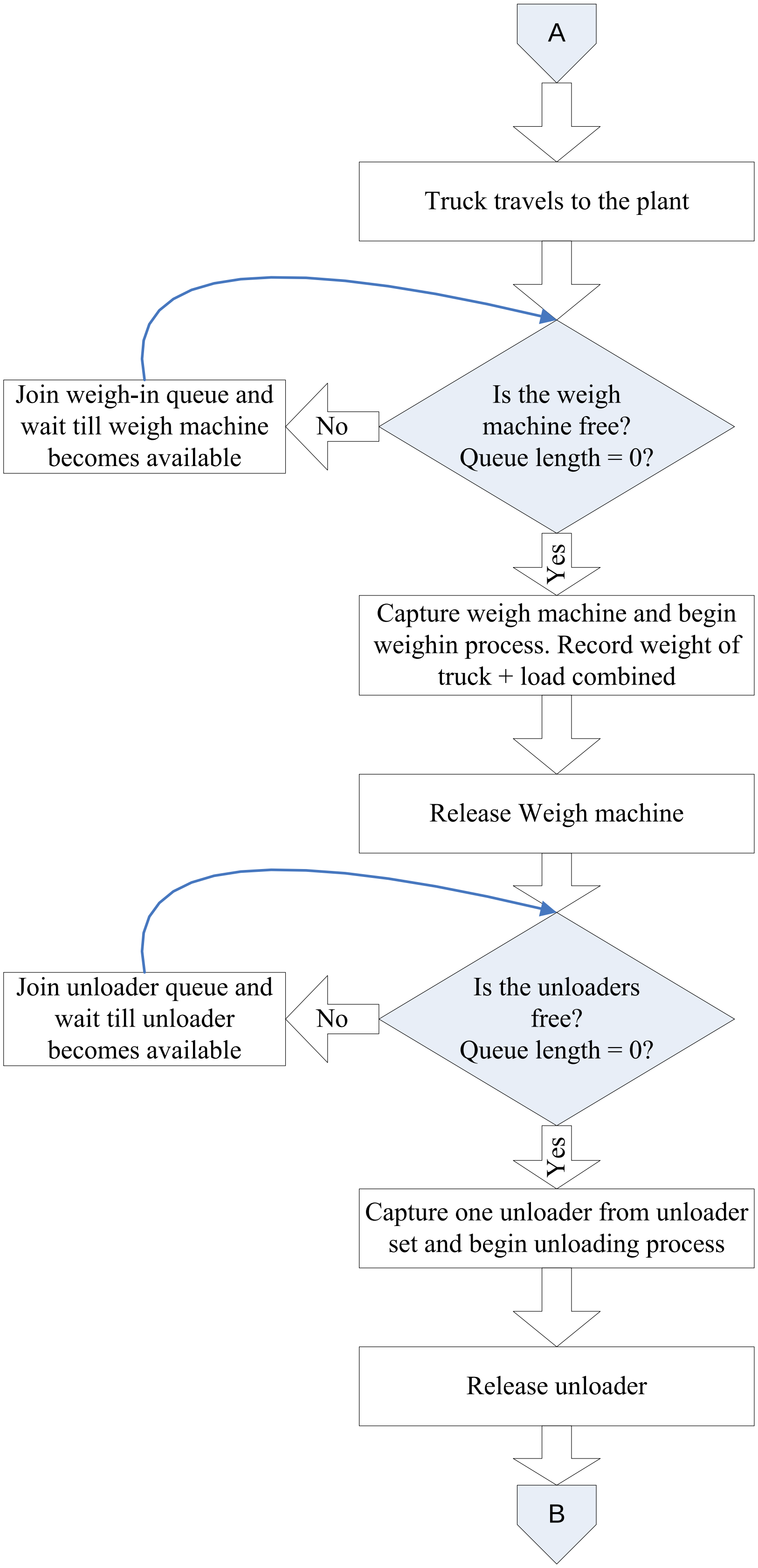


**Figure 7.16 Simulation Flowchart, continued from figure 7.15**

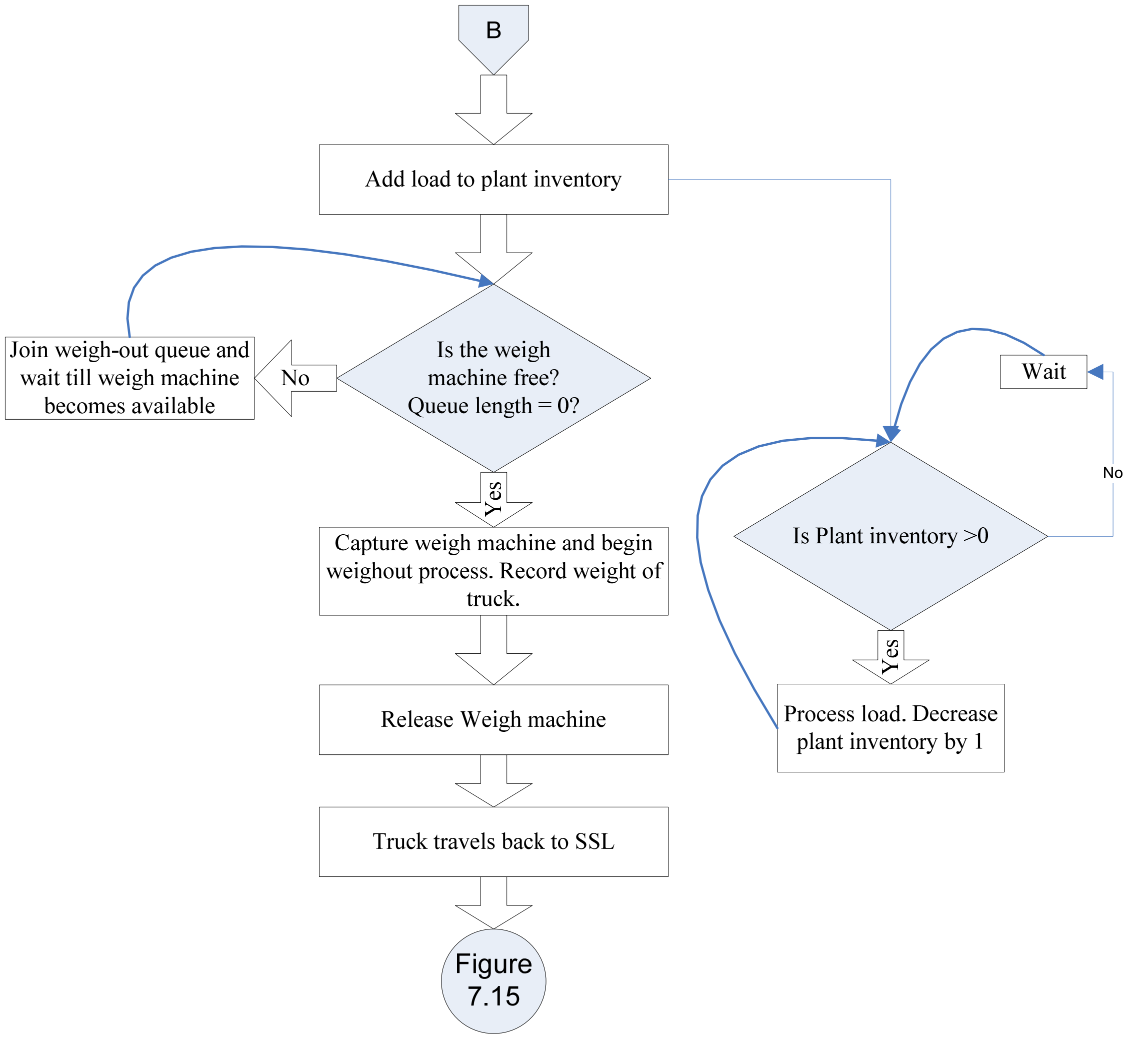


**Figure 7.17 Simulation flowchart, continued from figure 7.16**

Each time the event "Create 1" occurs, it transfers control to a VBA block with custom code. The VBA block opens the Excel files for a particular policy and loads the corresponding model parameters. Variables such as travel time from the plant to the SSL, number of trucks assigned to the loader, the number of loads available to the transportation system on that particular day from that specific SSL are read from the Excel file, and the discrete event model parameters are modified accordingly.

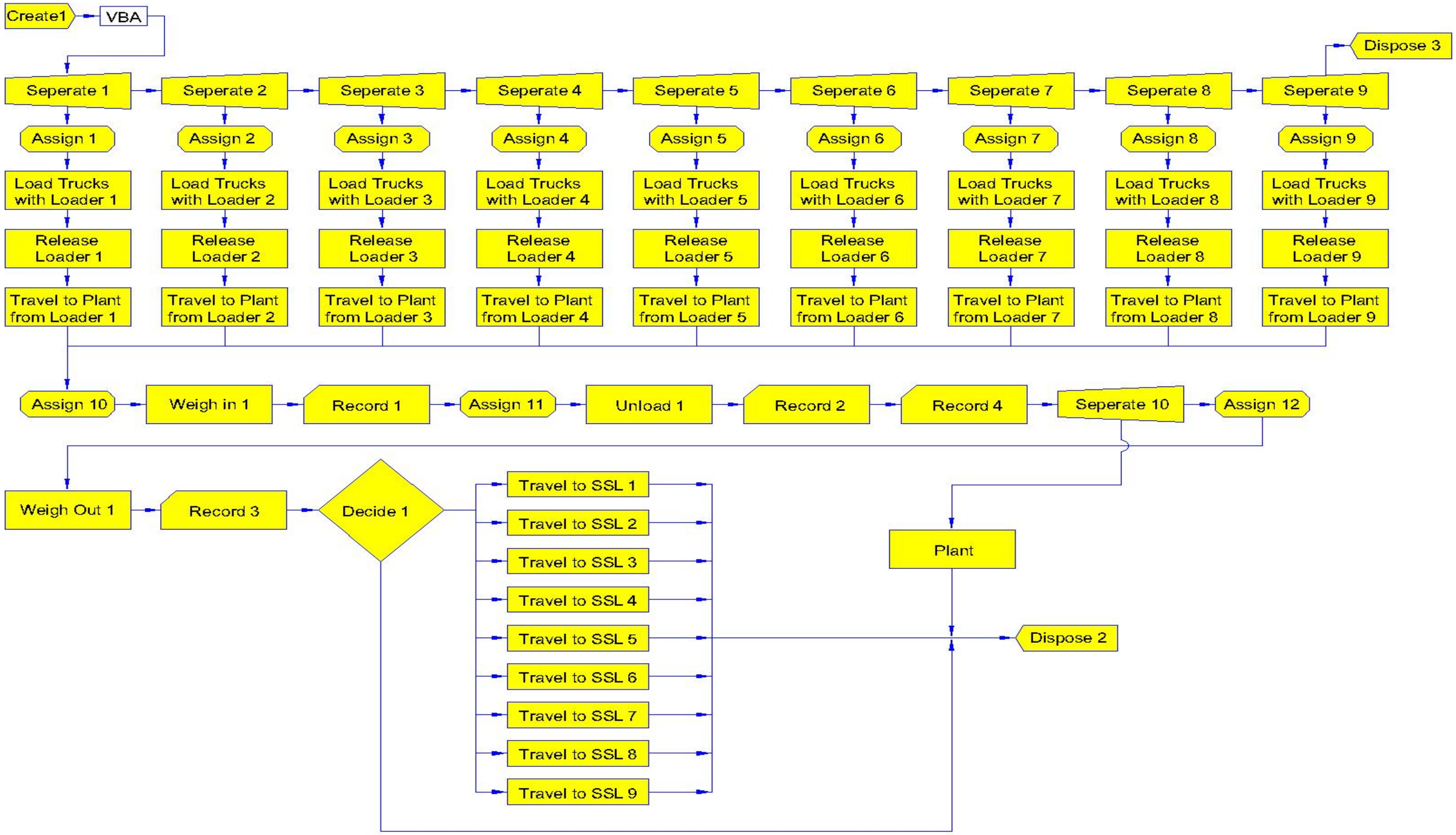


**Figure 7.18 Arena Simulation Model**

The next step is “Separate” processes. There is one Separate process for each of the nine loaders. This step creates either 15 or 0 loads at each SSL location, depending on the loads allocated to the SSL in the Excel files. A SSL with zero loads corresponds to a day when the loader moves, if the day does not correspond to a weekend. If the day is a weekend, the Separate process always creates zero available loads. Once the separate operation is completed, the model moves into nine identical sub-processes which load the trucks and sends them to the processing plant. The methodology is identical but the parameters of each individual sub-process are dependent on their corresponding loader parameters from the Excel policy files. The sub-process for Loader 1 is explained below and is identical to the sub-processes for loaders 2 to 9. The assign operation assigns the correct loader number for all the trucks passing through it depending on the loader number. This information is later used when returning the trucks to their original SSLs.

The “Load Truck with Loader1” process seizes one instance of resource Loader 1 and one instance of Truck from Truck resource set Truck 1. If either of these two resources is not available, the process waits till they become available. After the loading operation is complete, “Release Loader 1” releases Loader 1 and makes it available for the next load. If a truck is available when the loader release occurs, the “Load Truck with Loader1” event will immediately start next loading operation. Otherwise, it will wait till a Truck becomes available before starting the loading operation.

“Travel to Plant from Loader 1” process moves the truck and load from Loader 1 sub-process to the plant. The delay in this process depends on the travel time from the Excel file. Once the load reaches the plant, it captures the Weigh machine from the resource set. This operation was modeled using “Weigh In” process. After the process is complete, the load releases the weigh machine and captures an unloader from unloader resource set. The load then moves on to the plant queue where it waits untill it is used. The truck then moves to the “weigh out” process where it captures the weigh machine to record empty weight of the truck. The “Decide 1” process then sends the truck back to the SSL using “Travel to SSL” processes.

## 7.4 Simulation Output:

The simulation model was run for Policies 6 and 7 (50%, 45% and 40% land use rates) on a 2.4 GHz Core 2 Duo dual core processor with 2GB RAM. Each policy's schedule generated in Chapter 6 (Appendix A6) was used as the input parameters which controlled the travel times (SSL used), the number of trucks available for each loader and the number of loads available for pickup on each day.

Each run of the simulation model took less than 2 minutes. The model output data was collected into folders and VBA macros were run to convert the output data into Excel files and to generate utilization rates. The maximum number of hours a resource can operate was calculated as

$N_{WHS} = (N_{WW})(N_{WD})(N_{WHD})$, where (Equation 7.1)

$N_{WHS}$ = No. of working hours per season

$N_{WW}$ = No. of working weeks per season

= 25

$N_{WD}$ = No. of workdays per week

= 5

$N_{WHD}$ = No. of working hours per workday

= 12

The utilization rate for a resource was defined as (total number of hours the resource operated in one season)/(total possible operating hours). The data collected were at-plant inventory (Plant queue length), unloader process times, unloader used, Loader states and Truck states. The following two sub-sections (7.4.1 and 7.4.2) discuss the simulation results in detail.

### 7.4.1 Policy 6

Figure 7.19 shows the at-plant inventory level for Policy 6 with 50% land use rate. At 50% land use rate, the maximum number of loads at the plant was 384. This corresponds to a little over three days of plant demand (each day needs 117 loads). Figure 7.20 and Figure 7.21 show the at-plant storage for 45% and 40% land use rates. At 45% and 40%, the maximum numbers of loads were 345 and 362, respectively. The average inventory level was 206, 187, and 181 for 50%, 45% and 40% land use rates, respectively. As these figures show, the inventory level never drops to zero and the plant never stops due to insufficient loads during a season.

Figure 7.22 shows the number of loads delivered to the plant per week by Policy 6 at 50% land use rate. The maximum number of loads delivered was 675 and the minimum number delivered was 525 loads with an average of 595 loads per week. Figure 7.23 gives a “snapshot” the loads delivered to the plant every workday on a normal week. The maximum number of loads delivered per day was 120 loads and the minimum was 105 loads for the week shown (Week 4).

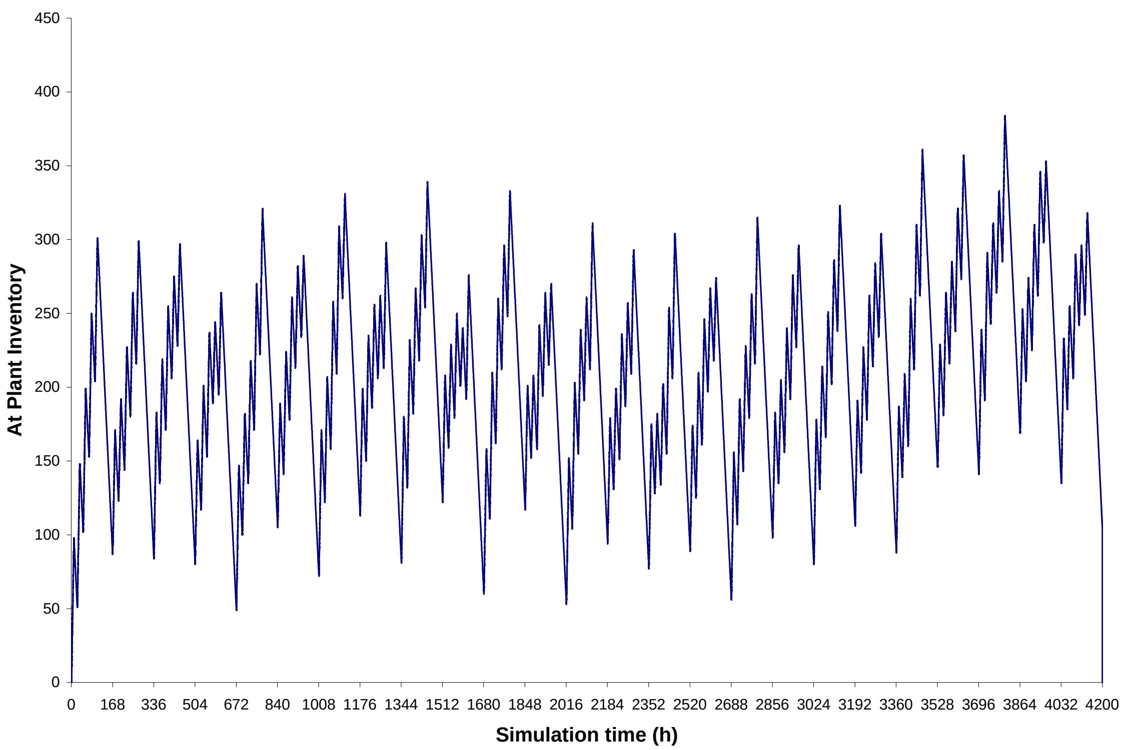


**Figure 7.19 At plant inventory level for Policy 6, 50% land use rate**

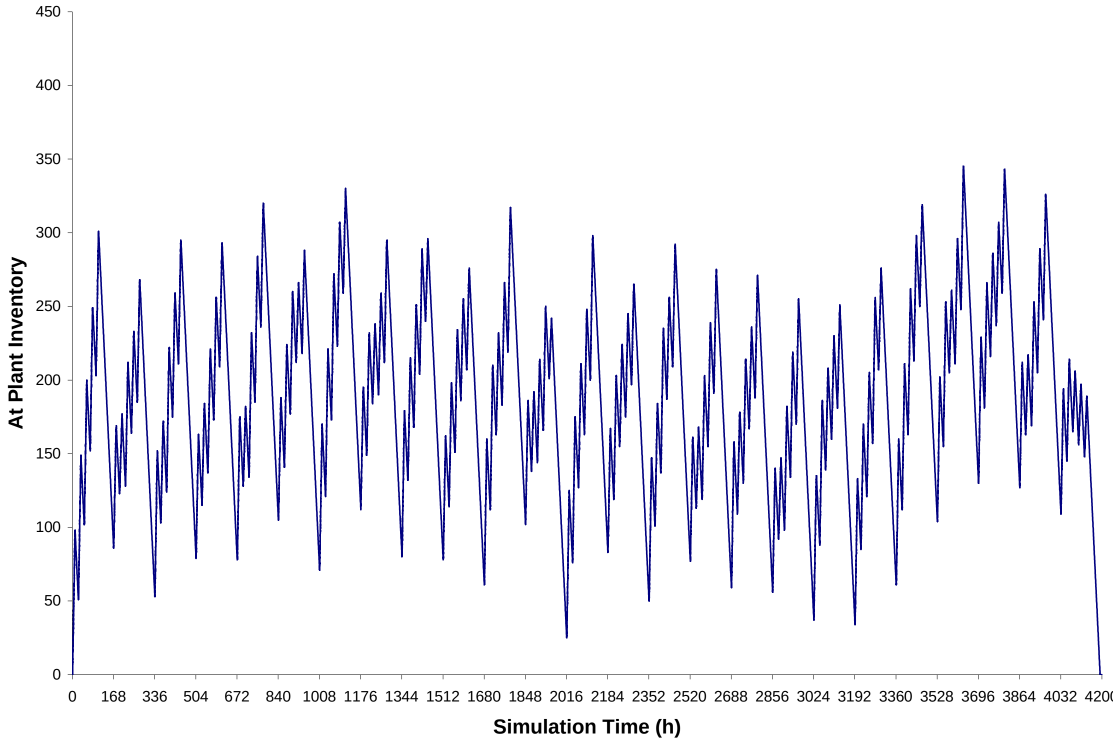


**Figure 7.20 At plant inventory level for Policy 6, 45% land use rate**

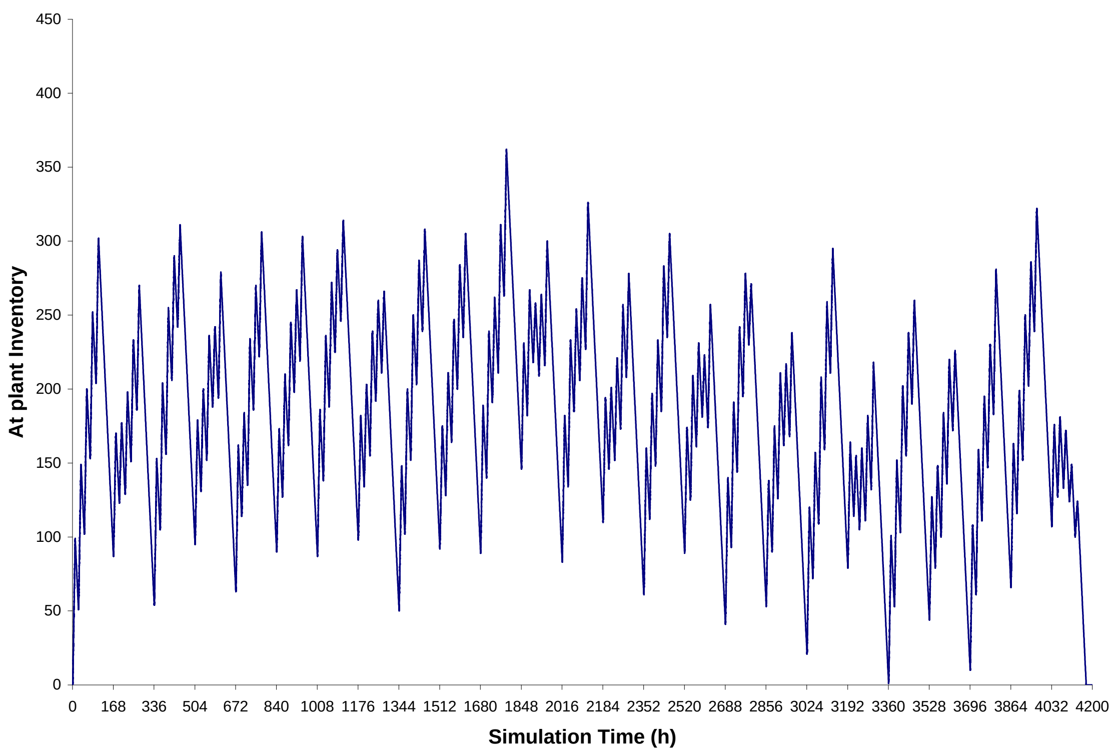


**Figure 7.21 At plant inventory level for Policy 6, 40% land use rate**

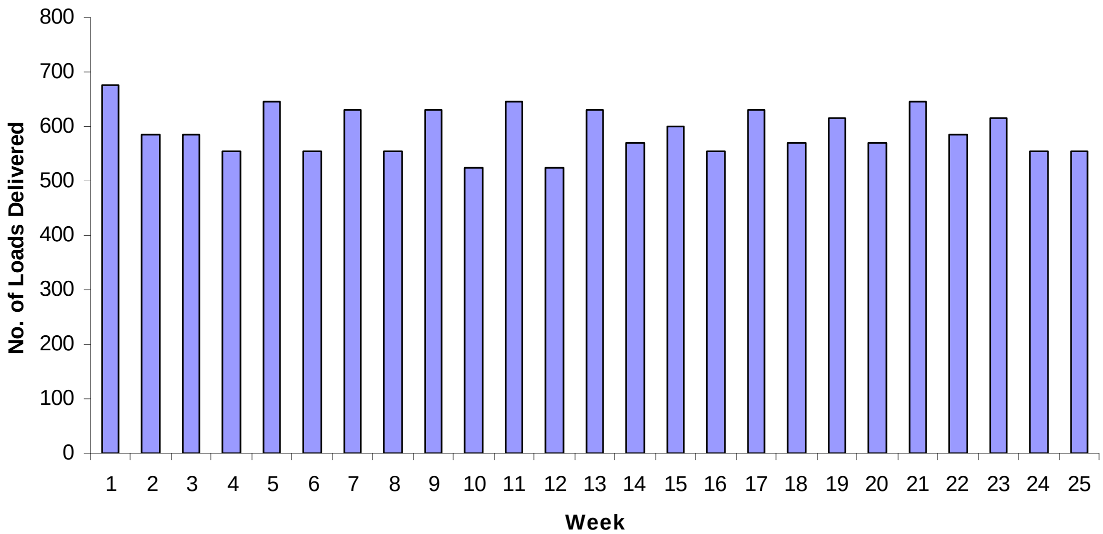


**Figure 7.22 Number of loads delivered to the plant per week, Policy 6, 50% land use rate**

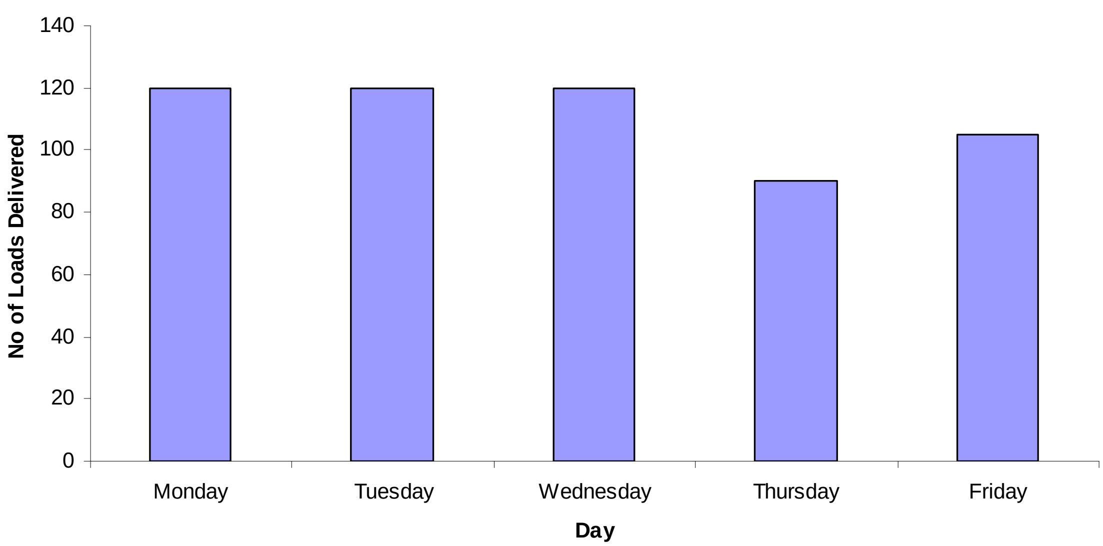


**Figure 7.23 Number of Loads delivered to the plant on week 4, Policy 6, 50% land use rate**

As the loads are delivered to the plant, the trucks need to be unloaded in a timely manner to avoid a build up. In this system, if the system three unloaders were used. UnLoader 1 has the highest priority and would be used to unload a truck when ever it is available. If

Unloader 1 is busy, then Unloader 2 is used. Unloader 3 has the lowest priority and would be used only if both Unloader 1 and 2 are busy.

Figure 7.24 shows the number of trucks waiting in the unloader queue on day 4 for Policy 6 with 50% land use rate. Day 4 has the highest number of loads delivered to the plant (135 Loads). The horizontal axis shows the time during which a change in unloader queue length occurred and the vertical axis shows the resulting queue length. The density of the bars show the frequency with which the unloader queue changed. A figure with high density of bars represents days during which more number of trucks were forced to wait in the queue. Figure 7.25 shows the number of trucks waiting in the unloader queue on a typical day (Day 11, 120 loads). The maximum number of trucks waiting was two. Figure 7.26 shows the number of trucks waiting in the unloader queue on a day with minimal loads delivered (Day 67, 75 loads), and the maximum number of trucks waiting in the queue was also two.

As the number of loads delivered to the plant increased, there was an increase in the number of trucks that reached the plant during a given period of time. This led to an increase in the number of trucks waiting for the unloaders to become available. The maximum number of trucks waiting in the queue during the entire season was four. Although the maximum number of trucks in unloader queue primarily depends on the number of trucks arriving at close intervals and depends heavily on the number of loads delivered, there were some instances when the trucks do arrive close enough even on a low delivery day to cause some queue buildup. As the density of the bar in the figures shows, a greater number of trucks were forced to use the unloader queue as the number of deliveries to the plant per unit time increased.

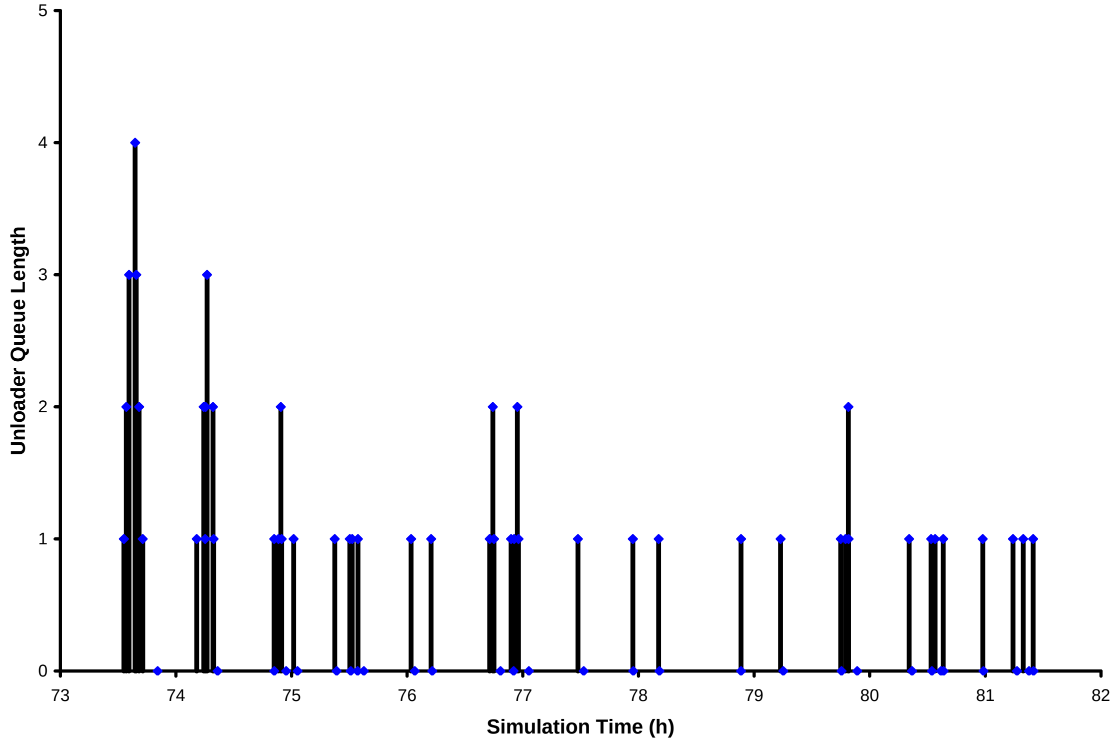


**Figure 7.24 Unloader Queue length when receiving maximum number of loads (135 loads) delivered to the plant on Day 4, Policy 6, 50% land use rate.**

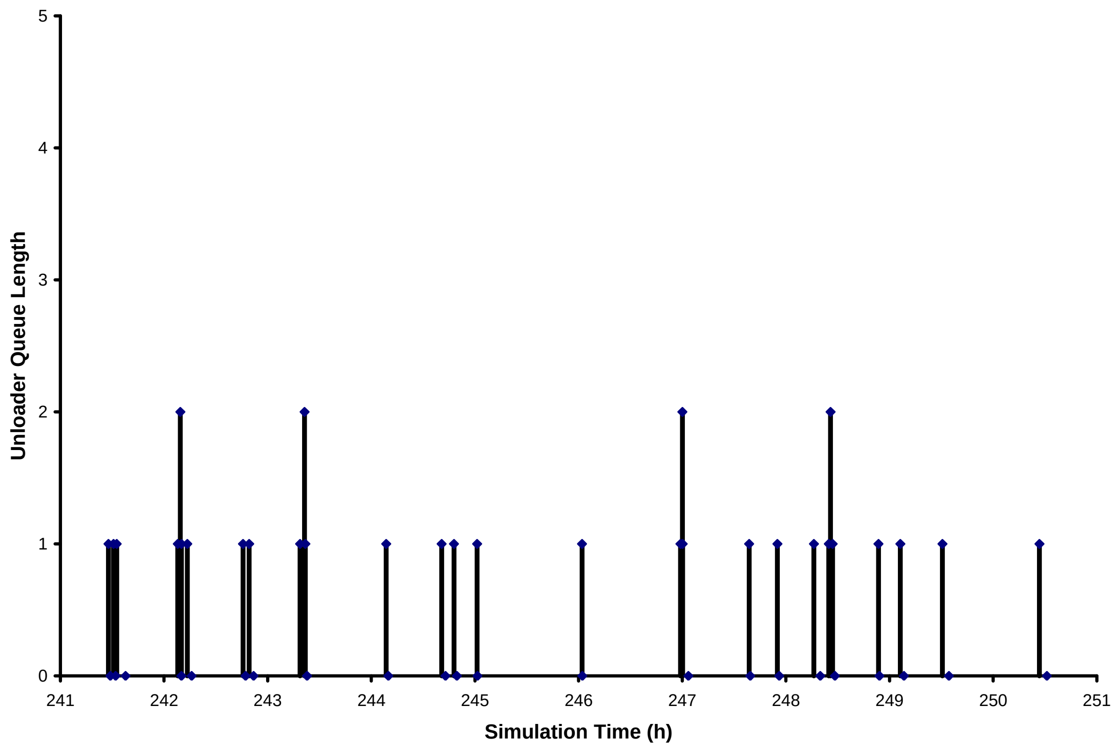


**Figure 7.25 Unloader Queue length when receiving a normal number of load (120 loads) delivered to the plant, Policy 6 on Day 11, 50% land use rate.**

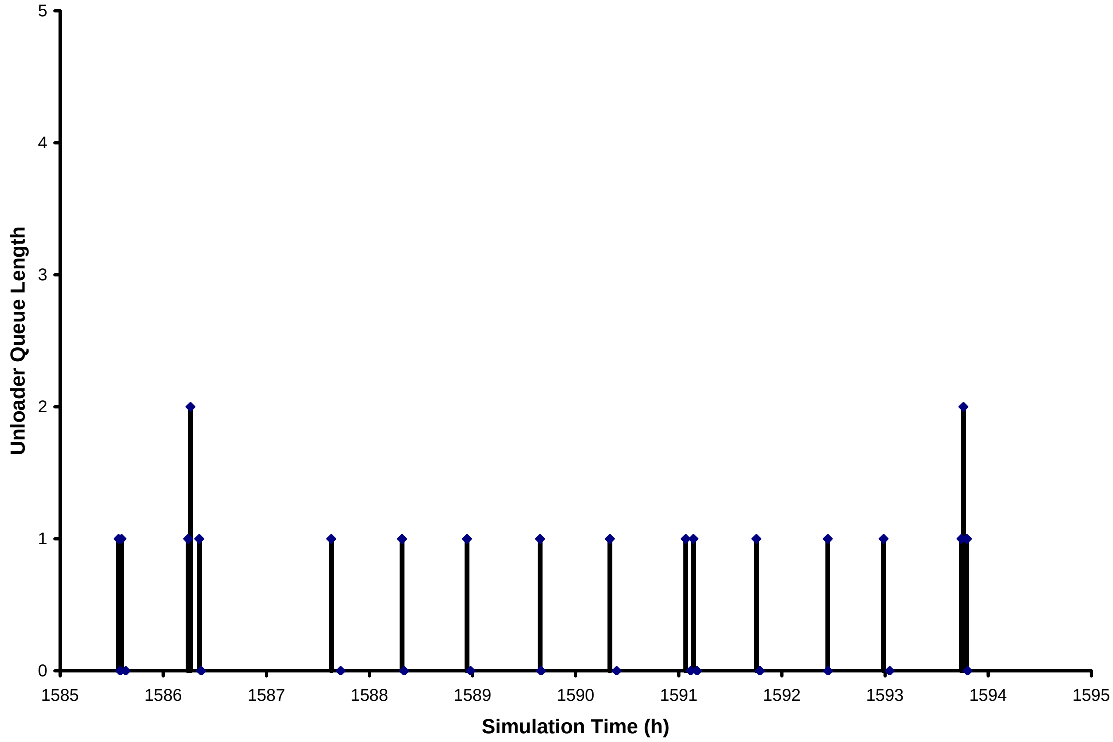


**Figure 7.26 Unloader Queue length when receiving the minimum number of load (75 loads) delivered to the plant, Policy 6 on Day 67, 50% land use rate.**

Table 7.1, Table 7.2,

Table 7.3 shows utilization hours and utilization rates of Loaders, Unloaders and Trucks in 50%, 45% and 40% land use rates, respectively. The average loader utilization rates were 75.3%, 75.5% and 79.9% for 50%, 45% and 40% land use rates, respectively. Loader 5 utilization values were lower as it uses part-time loader scheduling. The utilization rates remained nearly identical across all land use rates at 1,100 hrs per season as the number of loads remain the same.

As mentioned previously, the unloader utilization drops from 1,053 hours for Unloader 1 to 700 hours for Unloader 3 due to the priority between unloaders. The loader utilization remains constant, around 1,100 hours, except for Loader 5 which uses 550 hours. The unloader utilization rates were nearly constant across all three land use rates and were around 70%, 60% and 46% for unloaders 1, 2 and 3 respectively.

The maximum truck utilization rate was 81.2% and the minimum truck utilization rate was 36.4%. The average truck utilization rate was 68.1% and increased to 71.8% when the trucks assigned to part-time loader were dropped.

**Table 7.1 Policy 6 loader utilization summary**

| Resource | Utilization Times per season (h) | | | Avg. Utilization Rates (%) | | |
|---|---|---|---|---|---|---|
| | 50 % Land use rate | 45 % Land use rate | 40 % Land use rate | 50 % Land use rate | 45 % Land use rate | 40 % Land use rate |
| **Loader 1** | 1,123 | 1,083 | 1,076 | 74.9 | 72.2 | 71.7 |
| **Loader 2** | 1,121 | 1,086 | 1,073 | 74.7 | 72.4 | 71.5 |
| **Loader 3** | 1,083 | 1,083 | 1,056 | 72.2 | 72.2 | 70.4 |
| **Loader 4** | 1,083 | 1,099 | 1,062 | 72.2 | 73.3 | 70.8 |
| **Loader 5*** | 586 | 584 | 566 | 39.1 | 38.9 | 37.7 |
| **Loader 6** | 1,122 | 1,102 | 1,199 | 74.8 | 73.5 | 79.9 |
| **Loader 7** | 1,118 | 1,104 | 1,102 | 74.5 | 73.6 | 73.5 |
| **Loader 8** | 1,130 | 1,133 | 1,099 | 75.3 | 75.5 | 73.3 |
| **Loader 9** | 1,095 | 1,101 | 1,099 | 73.0 | 73.4 | 73.3 |

*Loader used part-time

**Table 7.2 Policy 6 Unloader utilization summary**

| Resource* | Utilization Times per season (h) | | | Avg. Utilization Rates (%) | | |
|---|---|---|---|---|---|---|
| | 50 % Land use rate | 45 % Land use rate | 40 % Land use rate | 50 % Land use rate | 45 % Land use rate | 40 % Land use rate |
| **UnLoader 1** | 1,053 | 1,055 | 1,050 | 70.2 | 70.3 | 70.0 |
| **UnLoader 2** | 906 | 893 | 892 | 60.4 | 59.5 | 59.5 |
| **UnLoader 3** | 700 | 682 | 692 | 46.7 | 45.5 | 46.1 |

*Priority given to #1 → #3

**Table 7.3 Policy 6 Truck utilization summary**

| Resource | Utilization Times per season (h) | | | Avg. Utilization Rates (%) | | |
|---|---|---|---|---|---|---|
| | 50 % Land use rate | 45 % Land use rate | 40 % Land use rate | 50 % Land use rate | 45 % Land use rate | 40 % Land use rate |
| **Truck 1** | 1,050 | 1,050 | 1,050 | 70.0 | 70.0 | 70.0 |
| **Truck 2** | 1,008 | 966 | 924 | 67.2 | 64.4 | 61.6 |
| **Truck 3** | 1,050 | 1,092 | 1,092 | 70.0 | 72.8 | 72.8 |
| **Truck 4** | 1,092 | 1,050 | 966 | 72.8 | 70.0 | 64.4 |
| **Truck 5*** | 630 | 546 | 546 | 42.0 | 36.4 | 36.4 |
| **Truck 6** | 1,176 | 1,218 | 1,092 | 78.4 | 81.2 | 72.8 |
| **Truck 7** | 1,134 | 1,176 | 1,176 | 75.6 | 78.4 | 78.4 |
| **Truck 8** | 1,092 | 1,134 | 1,134 | 72.8 | 75.6 | 75.6 |
| **Truck 9** | 1,008 | 1,050 | 1,092 | 67.2 | 70.0 | 72.8 |

*Trucks were assigned to part-time loader, Loader 5

### *7.4.2 Policy 7*

Figure 7.27 shows the at-plant inventory level for Policy 7 with 50% land use rate. At 50% land use rate, the maximum number of loads in at-plant inventory was 330. This corresponds to a little less than three days worth of usage at the plant (each day needs 117 loads). Figure 7.28 and Figure 7.29 show the at-plant storage for 45% and 40% land use rates. At 45% and 40%, the maximum numbers of loads were 342 and 301, respectively. The average number of loads at the plant was 171, 172 and 152 loads for 50%, 45% and 40% land use rates, respectively.

Figure 7.30 shows the number of loads delivered to the plant per week in Policy 7, 50% land use rate during a season. The maximum number of loads delivered was 600 and the minimum loads delivered were 465, with an average of 520 loads per week. Figure 7.31 shows the number of loads delivered to the plant per day on a normal work week (Week 5). The maximum number of loads delivered was 135 and the minimum number of loads delivered was 120.

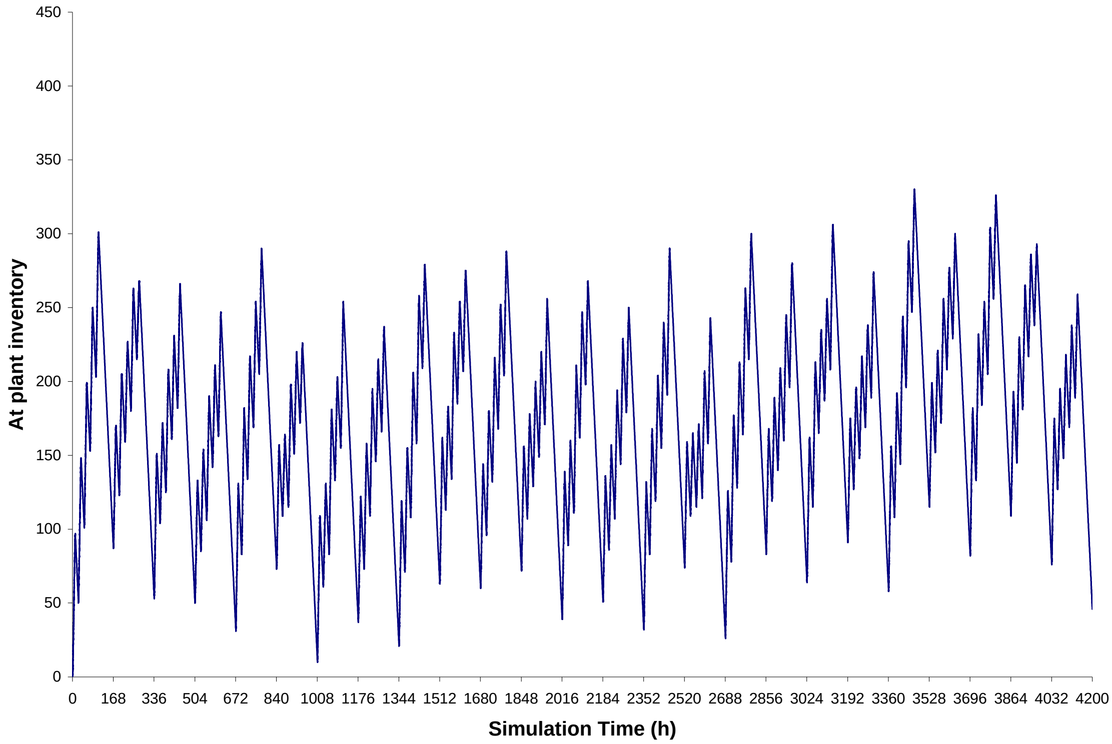


**Figure 7.27 At plant inventory level for Policy 7, 50% land use rate**

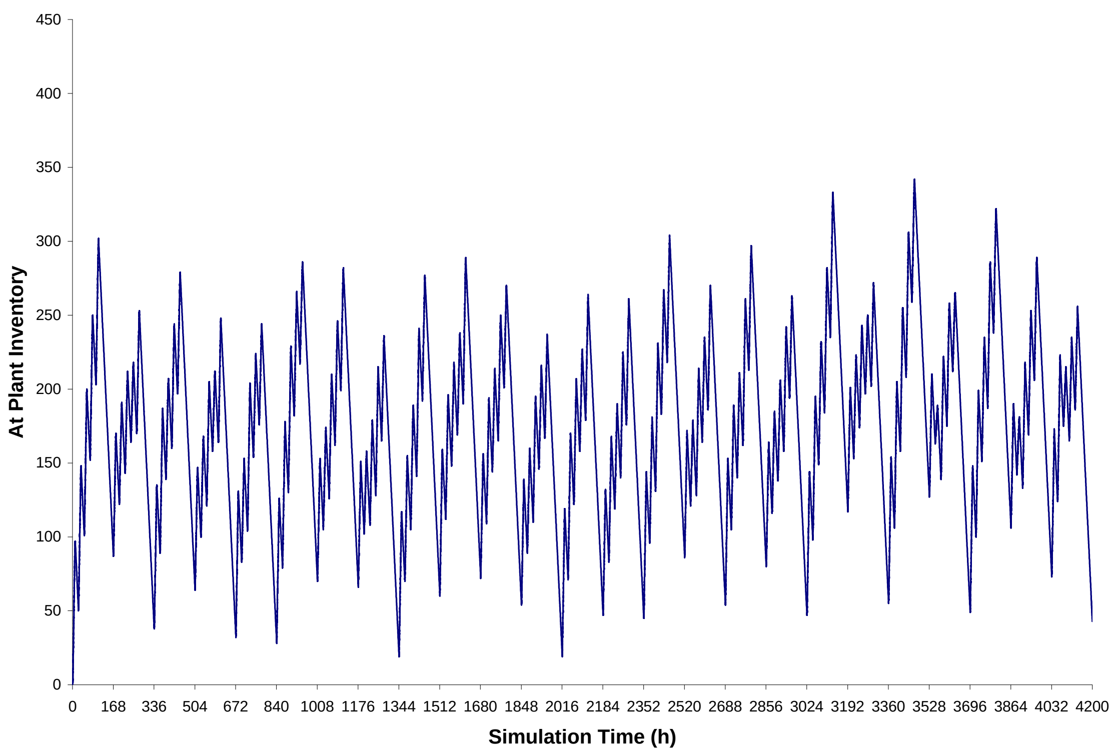


**Figure 7.28 At plant inventory level for Policy 7, 45% land use rate**

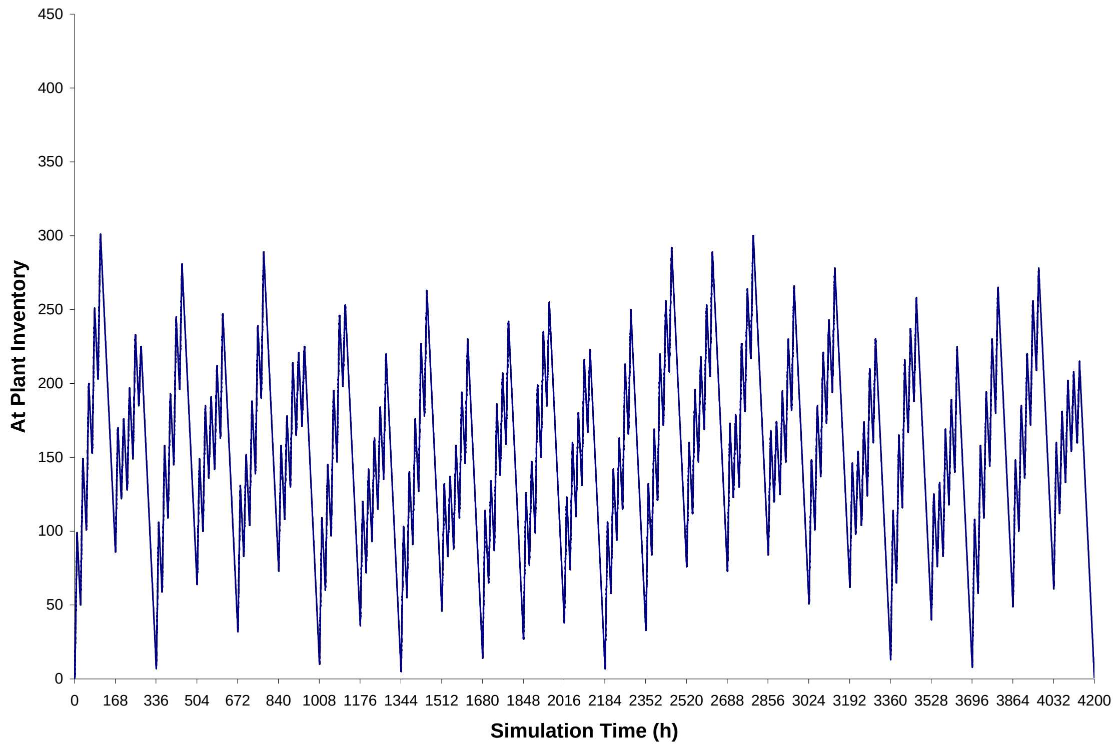


**Figure 7.29 At plant inventory level for Policy 7, 40% land use rate**

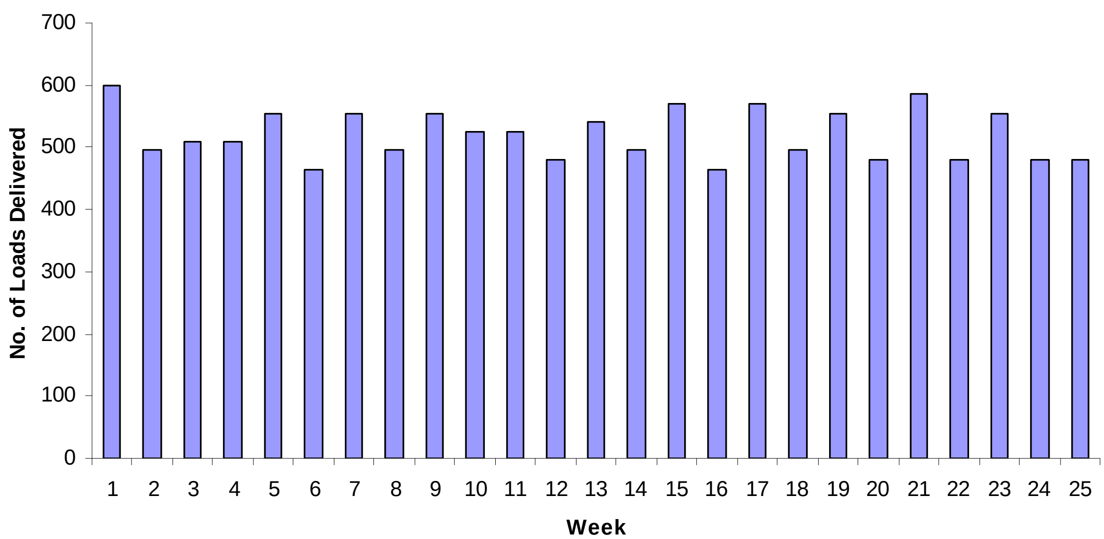


**Figure 7.30 Number of Loads delivered to the plant per week, Policy 7, 50% land use rate**

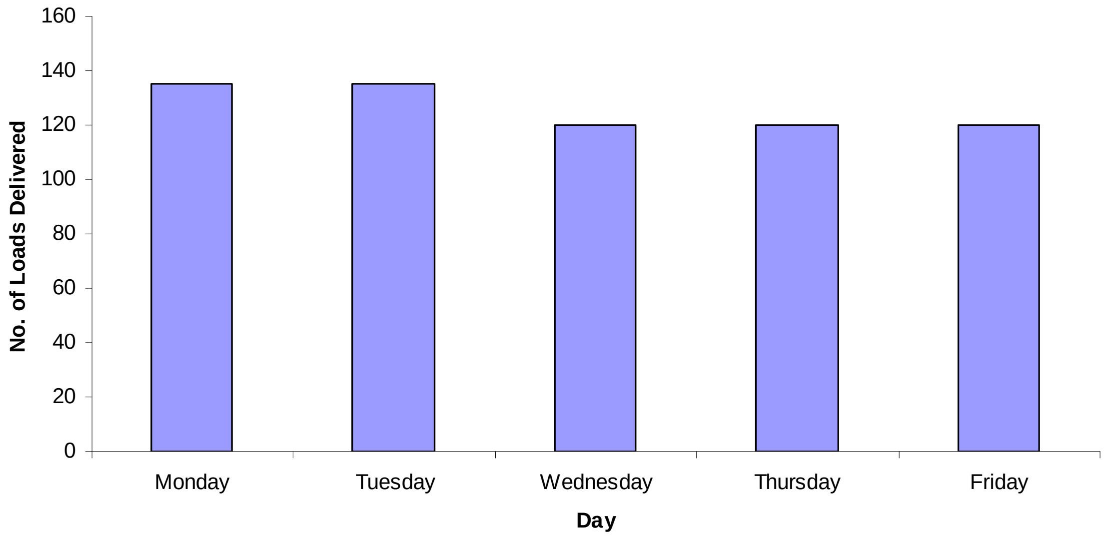


**Figure 7.31 Number of Loads delivered to the plant on week 5, Policy 7, 50% land use rate**

Figure 7.32 shows the number of trucks waiting in the unloader queue for Policy 7 with 50% land use rate on the day with maximum number of deliveries (Day 15, 135 loads). The horizontal axis shows the time during which a change in unloader queue length occurred and the vertical axis shows the resulting queue length. The density of the bars show the frequency with which the unloader queue changed. A figure with high density of bars represents days during which more trucks were forced to wait in the queue. The maximum number of trucks waiting in the unloader queue was 5.

Figure 7.33 shows the unloader queue length on a normal day (Day 8, 120 Loads). The maximum number of trucks waiting for the unloaders was 3. Figure 7.34 shows the unloader queue length on a day with minimum loads delivered (Day 11, 75 loads). The maximum queue length was 3. As mentioned previously, although the maximum number of trucks waiting in the unloader queue is highly correlated to the number of loads delivered to the plant, there are instances, even during days with low deliveries, where trucks from different SSLs reach the plant at or almost the same time. This causes a temporary spike in the unloader queue. This temporary increase does not significantly affect the transportation system as designed for this simulation. However, if the plant had only two unloaders, then longer unloading queues may result. There is a tradeoff between the cost of operating an extra unloader and lost truck productivity.

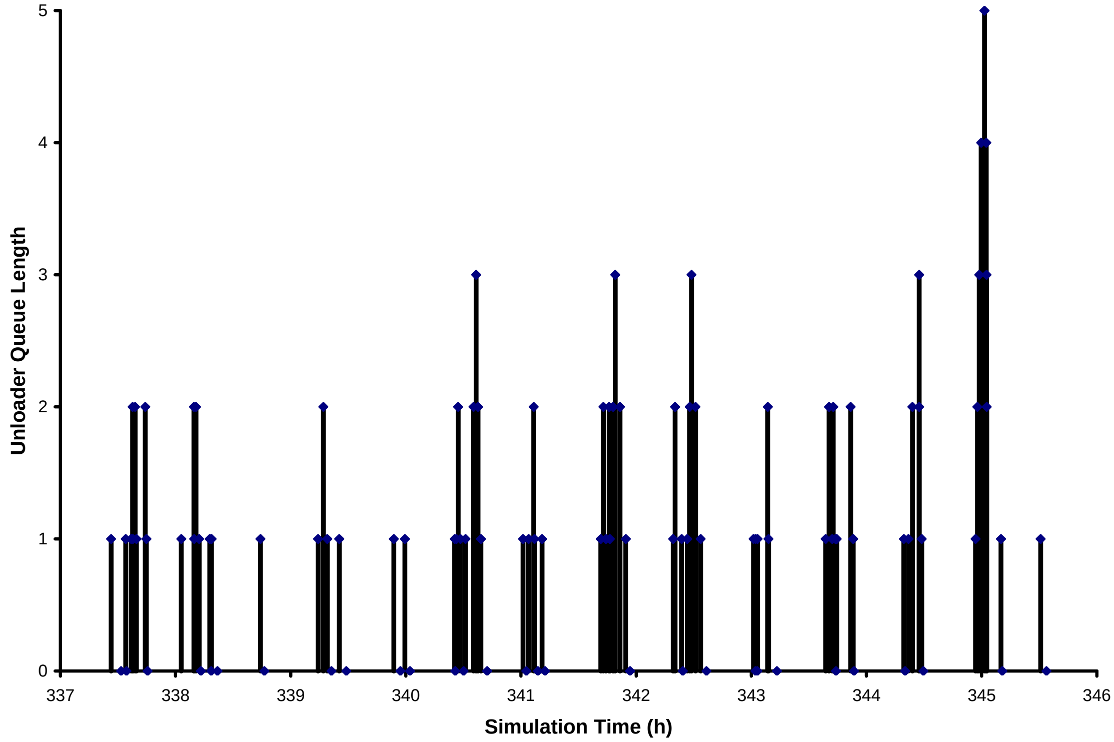


**Figure 7.32 Unloader Queue length when receiving maximum number of loads (135 loads) delivered to the plant, Policy 7, 50% land use rate (Day 15)**

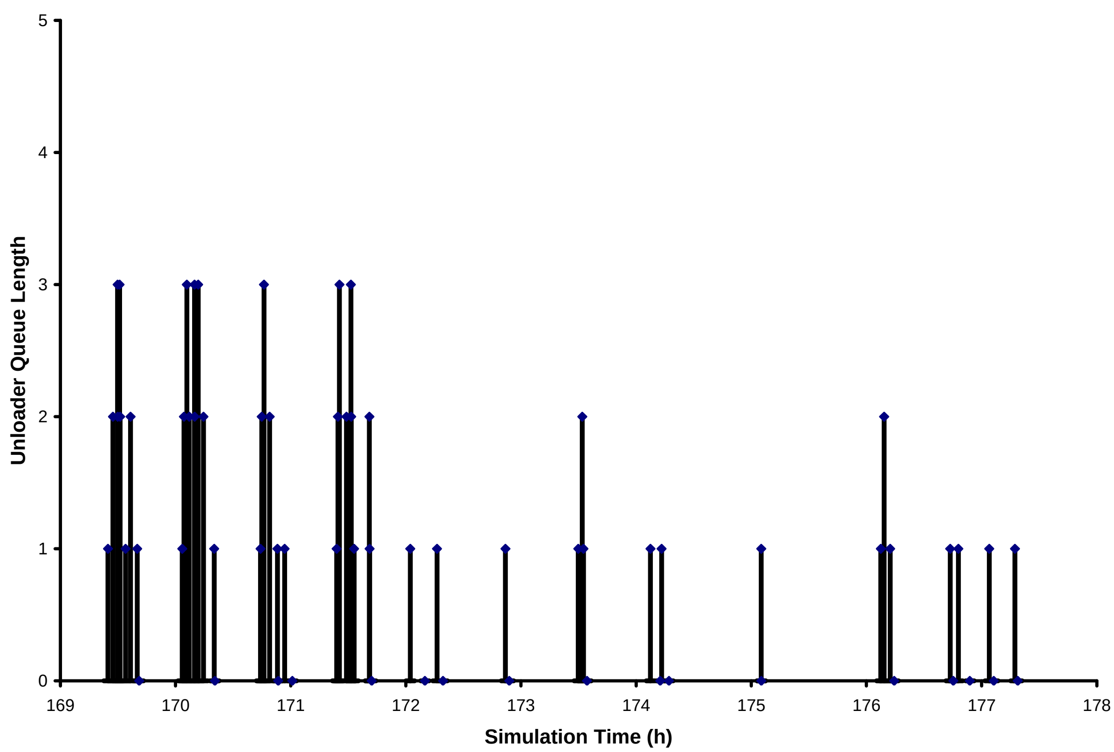


**Figure 7.33 Unloader Queue length when receiving normal number of loads (120 loads) delivered to the plant, Policy 7, 50% land use rate (Day 8)**

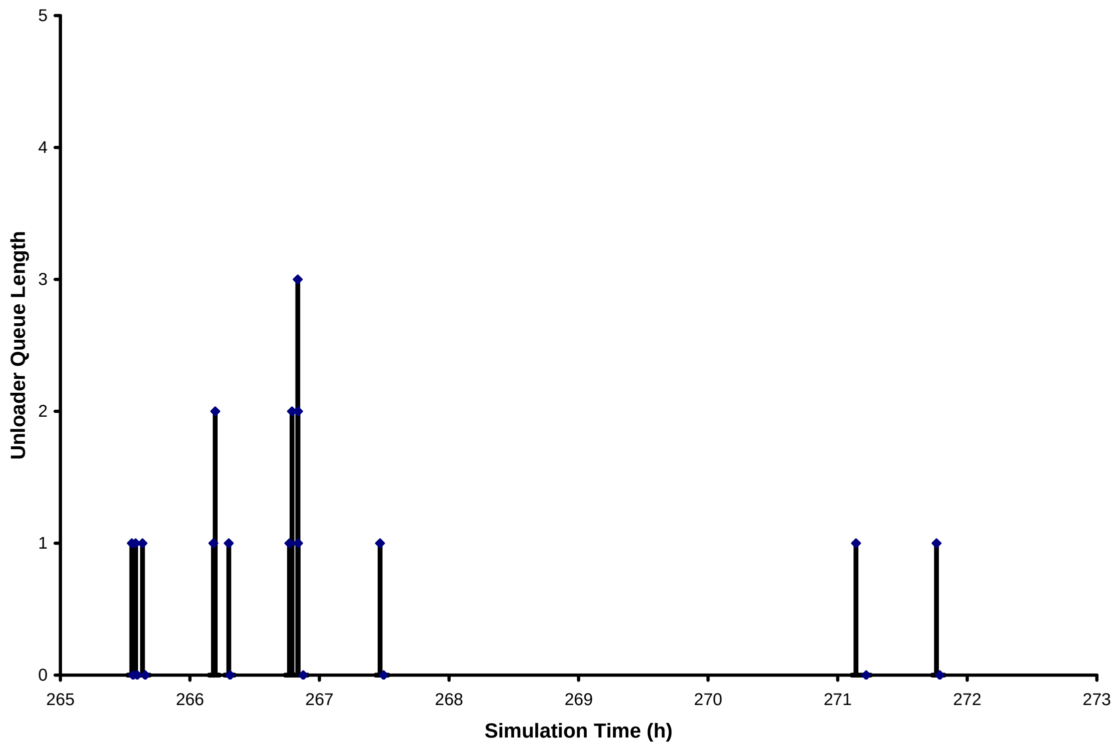


**Figure 7.34 Unloader Queue length when receiving maximum number of loads (75 loads) delivered to the plant, Policy 6, 50% land use rate (Day 11)**

Table 7.4, Table 7.5 and Table 7.6 shows the utilization numbers for resources for 50%, 45% and 40% land use rates. As mentioned previously, the utilization rate for a resource was defined as the ratio of total number of hours the resource operated in one season to the total possible operating hours. The maximum loader utilization rates were 76%, 80% and 75.5% for 50%, 45% and 40% land use rates, respectively. The utilization rates were similar to Policy 6, with loader utilization rates around 1,100 h for Loader 1 to 8. Loader 9, which followed a part-time loader policy, was around 580 hours.

The unloader utilization drops from 1,059 hours for unLoader 1 to 708 hours for unLoader 3 due to the priority between unloaders. The unloader utilization rates were nearly constant across all three land use rates and were around 70%, 60% and 47% for unloaders 1, 2 and 3 respectively. This matches the utilization rates of Policy 6. The maximum truck utilization rate was 78.4% and the minimum was 39.2%. The average truck utilization rate was 68.3% and increased to 71.8% when trucks assigned to part-time loader were not considered. These utilization numbers were again very similar as Policy 6.

**Table 7.4 Policy 7 loader utilization summary**

| Resource | Utilization Times per season (h) | | | Avg. Utilization Rates (%) | | |
|---|---|---|---|---|---|---|
| | 50 % Land use rate | 45 % Land use rate | 40 % Land use rate | 50 % Land use rate | 45 % Land use rate | 40 % Land use rate |
| **Loader 1** | 1,114 | 1,107 | 1,082 | 74.3 | 73.8 | 72.1 |
| **Loader 2** | 1,121 | 1,082 | 1,075 | 74.7 | 72.1 | 71.7 |
| **Loader 3** | 1,112 | 1,200 | 1,101 | 74.1 | 80.0 | 73.4 |
| **Loader 4** | 1,140 | 1,137 | 1,119 | 76.0 | 75.8 | 74.6 |
| **Loader 5** | 1,098 | 1,084 | 1,112 | 73.2 | 72.3 | 74.1 |
| **Loader 6** | 1,062 | 1,091 | 1,072 | 70.8 | 72.7 | 71.5 |
| **Loader 7** | 1,104 | 1,085 | 1,132 | 73.6 | 72.3 | 75.5 |
| **Loader 8** | 1,085 | 1,073 | 1,072 | 72.3 | 71.5 | 71.5 |
| **Loader 9*** | 585 | 573 | 623 | 39.0 | 38.2 | 41.5 |

*Loader 9 was used part-time

**Table 7.5 Policy 7 unloader utilization summary**

| Resource* | Utilization Times per season (h) | | | Avg. Utilization Rates (%) | | |
|---|---|---|---|---|---|---|
| | 50 % Land use rate | 45 % Land use rate | 40 % Land use rate | 50 % Land use rate | 45 % Land use rate | 40 % Land use rate |
| **UnLoader 1** | 1,059 | 1,060 | 1,056 | 70.6 | 70.7 | 70.4 |
| **UnLoader 2** | 904 | 906 | 914 | 60.3 | 60.4 | 60.9 |
| **UnLoader 3** | 708 | 711 | 704 | 47.2 | 47.4 | 46.9 |

*Priority given to #1 → #3

**Table 7.6 Policy 7 Truck utilization summary**

| Resource | Utilization Times per season (h) | | | Avg. Utilization Rates (%) | | |
|---|---|---|---|---|---|---|
| | 50 % Land use rate | 45 % Land use rate | 40 % Land use rate | 50 % Land use rate | 45 % Land use rate | 40 % Land use rate |
| **Truck 1** | 1,092 | 1,092 | 1,050 | 72.8 | 72.8 | 70.0 |
| **Truck 2** | 1,176 | 1,092 | 1,092 | 78.4 | 72.8 | 72.8 |
| **Truck 3** | 1,050 | 1,092 | 1,050 | 70.0 | 72.8 | 70.0 |
| **Truck 4** | 1,176 | 1,176 | 1,176 | 78.4 | 78.4 | 78.4 |
| **Truck 5** | 1,050 | 1,008 | 1,050 | 70.0 | 67.2 | 70.0 |
| **Truck 6** | 1,050 | 1,050 | 1,050 | 70.0 | 70.0 | 70.0 |
| **Truck 7** | 1,050 | 1,008 | 1,092 | 70.0 | 67.2 | 72.8 |
| **Truck 8** | 1,050 | 1,050 | 1,050 | 70.0 | 70.0 | 70.0 |
| **Truck 9*** | 588 | 588 | 630 | 39.2 | 39.2 | 42.0 |

*Trucks were assigned to part-time loader, Loader 9

## *7.5 Sensitivity Analysis*

The logistic system depends heavily on truck travel times. If the truck gets delayed on a regular basis, the plant may not be able to operate without interruption. The simulation model was modified to operate the system with variable truck travel time to study its behavior when random delays occur. On the other hand, if the plant speeds up its processing time, the plant may run out of inventory although the transport system may be supplying loads at designed capacity.

### *7.5.1 Truck travel time:*

The travel component of the simulation model was modified and the calculated travel time between a SSL and the plant was replaced with a triangular distribution. It is expected that the travel component will not vary significantly from the calculated values and so, the calculated travel times that were used for the previous analysis was used as the mode for the triangular distribution. The minimum value of the distribution was set at (0.9)( Calculated travel time) and the maximum value was set at (1.1)( Calculated travel time). This causes the trucks to take longer to reach the plant on some instances and to reach the plant faster on others. The model was also simulated with the maximum value set at (1.2)( Calculated travel time).

#### *7.5.1.1 Policy 6 and 7 results:*

Figure 7.35 and Figure 7.36 shows the inventory level at the plant inventory level when Policies 6 and 7 were simulated with modified travel times with the maximum value set at (1.1)(Calculated travel time). With an occasional higher travel time, the trucking system takes longer to move the loads to the plant, but the plant has enough inventory and there was enough unused resource times for loaders that the plant remained unaffected. Even if the maximum travel time value in the triangular distribution was changed to (1.2)(Calculated travel time), the plant did not suffer from shortages. This clearly shows that the transportation system was not sensitive to small changes in truck travel times.

It should be noted that any increase in travel time will make the trucks run longer as they will remain on the road for longer hours. This would normally increases the time between load cycles by the loader, unless there is always a truck waiting for the loader to complete its operation at the SSL. The logistic system was designed such that the loaders at the SSLs are never waiting for the trucks, but the trucks were allowed to wait on the loaders. This introduces some extra waiting times for the trucks under normal operations.

Any increase in truck travel time will first reduce the time trucks wait for the loader to become available. Only after this waiting time is exhausted, the loader begins to wait for the trucks to become available and thereby cause a decrease in the number of loads delivered to the plant by the system on a given day. Even with a 20% increase in travel times, there was enough existing truck waiting times to allow for uninterrupted operation of the loaders.

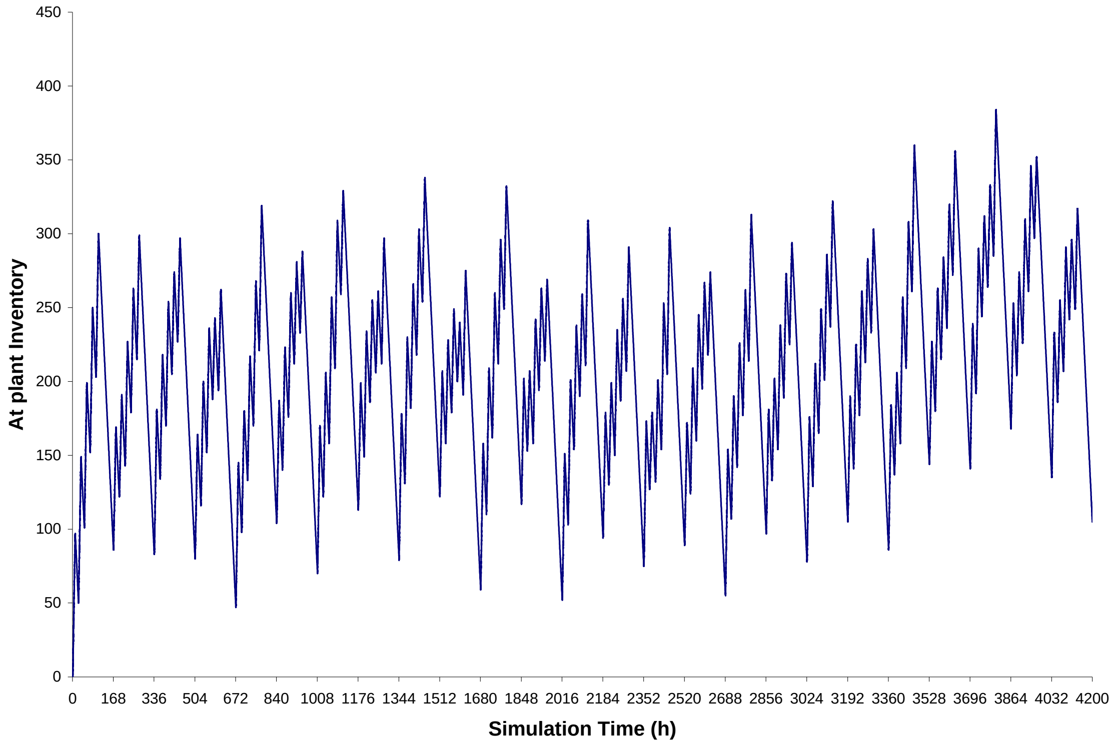


**Figure 7.35 At plant inventory level, Policy 6 with modified travel time, 50% land use rate**

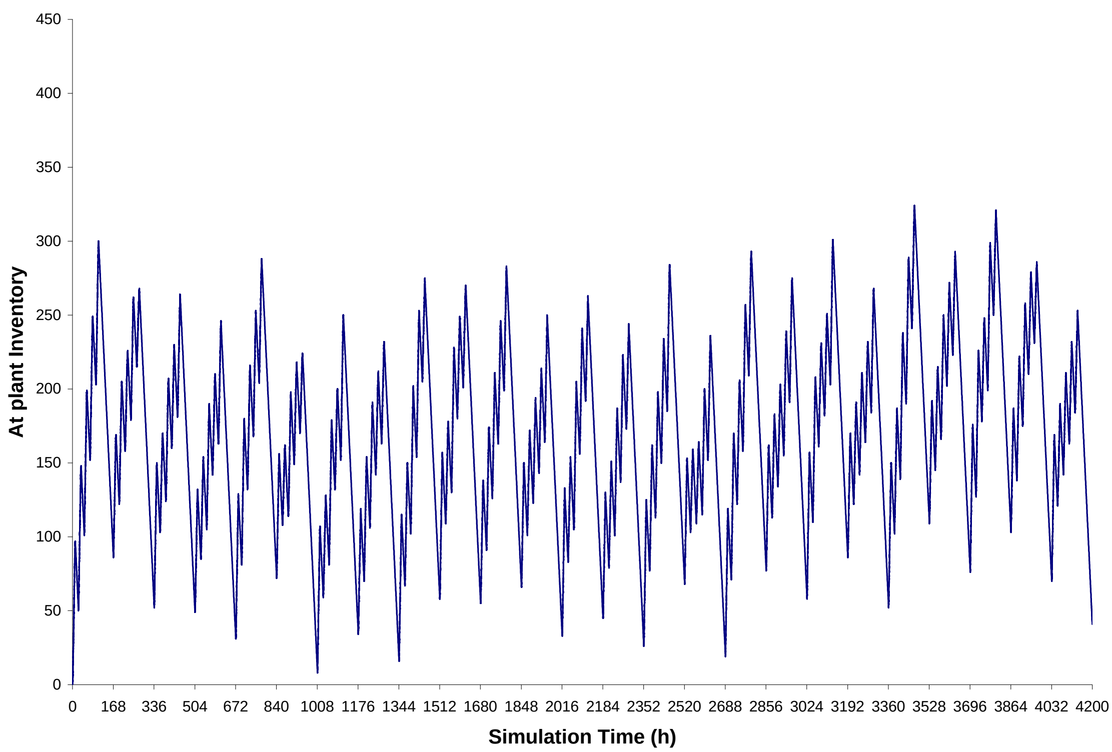


**Figure 7.36 At plant inventory level, Policy 7 with modified travel time, 50% land use rate**

### 7.5.2 Plant processing time:

The plant when operating at capacity (50 Mg/h) uses 3.5 loads per hour. This corresponds to 17.14 min per load. The simulation model was modified to run with process times of 17 min and 17.28 min to study its behavior when the process time is no longer at designed specification. This change in processing time corresponds to an increase or decrease of 0.03 loads per hour by the plant.

Figure 7.37 and Figure 7.38 show the inventory level at the plant when the processing time decreases from 17.14 min per load to 17 min for policies 6 and 7 respectively. As the plant processing time decreases, the number of loads consumed per hour goes up. The decrease of 0.14 min corresponds to an increased consumption of 0.03 loads per hour. Even at such low increase, the plant quickly runs out of material to process and stops. In Policy 6 with 50% land use rate, the plant stops two times during the season. Policy 7 on the other hand, stops five times during the season. Moreover, there are times when the inventory level drops below 50 loads. If there were delays in truck transportation during these times, the plant may not be able to run and may result in additional plant stops.

The behavior of at-plant inventory shows that the system is highly sensitive to changes in plant processing times, especially when there is an increase in the number of loads consumed per hour. Although this can be construed as the behavior of a transportation system highly tuned to the plant requirement, it should be pointed out that the transportation system still has some additional capacity that was not utilized. The part-time loader in the system can be tasked to move additional loads to the plant during or before a projected load shortage. This will help in running the plant without interruptions and without significant changes to the transportation system or its schedule. These additional loads can be moved either from additional SSLs that were not used in the initial policy or, by moving up the operational days of the part-time loader into idle weeks.

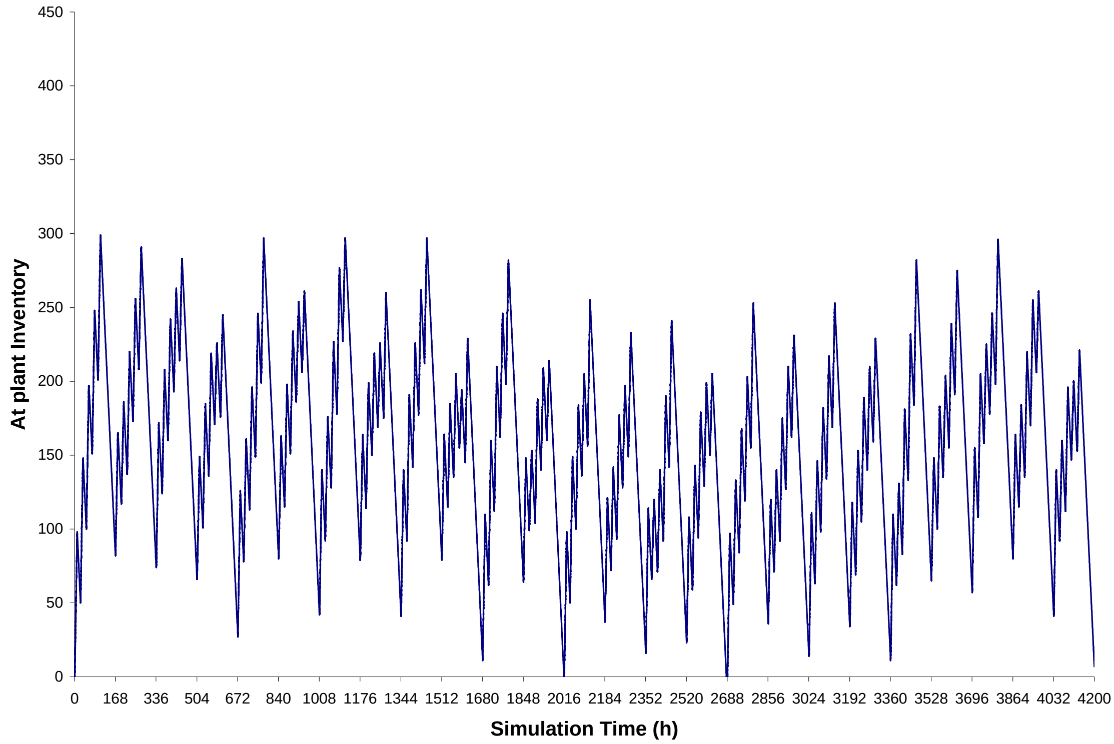


**Figure 7.37 Policy 6 with decreased processing time (17 min), 50% land use rate**

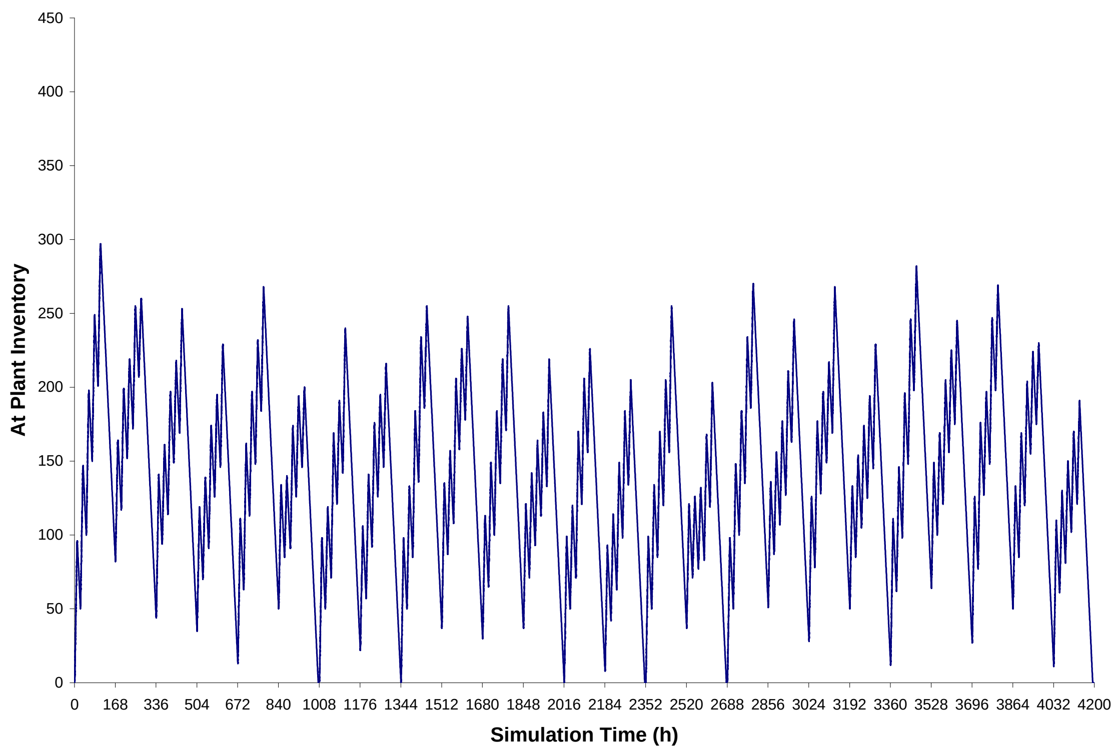


**Figure 7.38 Policy 7 with decreased processing time (17 min), 50% land use rate**

Figure 7.39 and Figure 7.40 show the inventory level at the plant as the processing time increases from 17.14 min to 17.28 min for Policies 6 and 7, respectively. As the processing time goes up, the plant does not consume as many loads per hour as it was at designed specification. This leads to a build up of inventory at the plant and a corresponding increase in storage area. Other than this inventory build up, the plant does not suffer from any down time due to this increase in processing times.

The increase in inventory level can be addressed by dropping one or more SSLs from the scheduled list of the part-time loader. When dropping SSLs, the first priority should be SSLs that use the largest number of trucks. Such a policy can reduce the maximum number of trucks used by the system and thereby reduce the overall system cost.

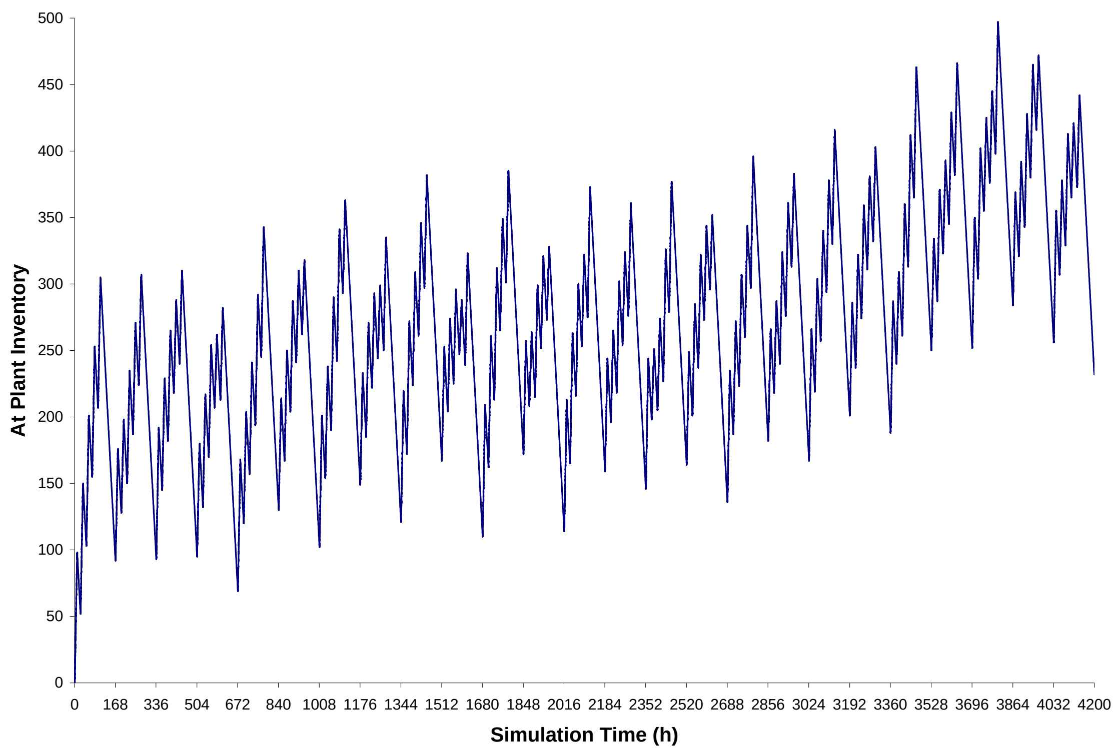


**Figure 7.39 Policy 6 with increased processing time (17.28 min), 50% land use rate**

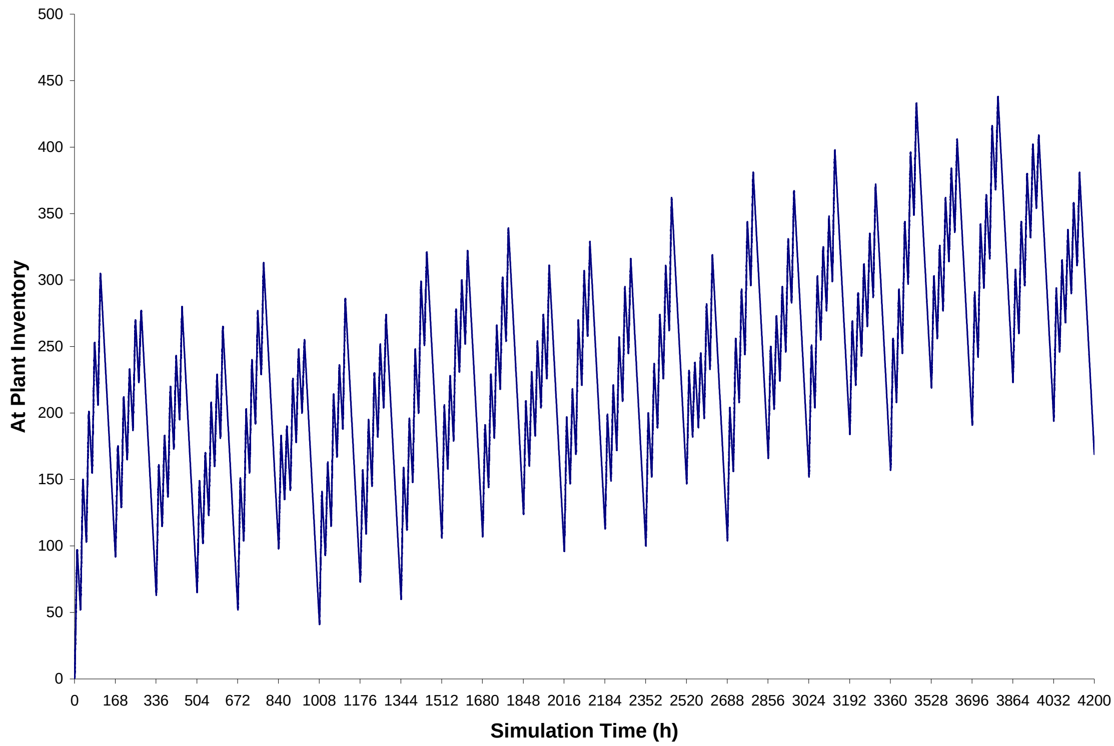


**Figure 7.40 Policy 7 with increased processing time (17.28 min), 50% land use rate**

## *7.6 Economic Analysis:*

The cost to deliver biomass to the plant includes costs from individual operations, such as road travel cost, loader transport cost and from capital cost of owning the resources such as Trucks, Loaders and Unloaders. The overall cost can be divided into cost components based on the resource that is being used. The following section describes these cost components and their contribution to the overall biomass delivery cost using the present system.

### ***7.6.1 Truck Cost:***

There are two subcomponents to truck cost, namely, truck ownership cost and truck fuel cost. The truck ownership component includes capital cost of the truck, routine maintenance (tires, brakes, lubrication), and the labor (driver) cost. The fuel cost only includes the cost of the fuel. It was assumed that the truck will always include a driver and this component remains even when the truck was idle on any particular day. That is, the driver cannot be hired and fired as needed. It is also assumed that the trucks used in this system do not have any other productive tasks that they can perform when they are not needed.

The total truck ownership cost remains the same during a season and is a function of the maximum number of trucks used by the policy during a season. The ownership cost was assumed to be $450 per day, including a driver (Cundiff, 2007). In this system, each truck operates five days per week and for 25 weeks per season. Table 7.7 shows the maximum number of trucks used by policies 6 and 7 during the season and their corresponding cost figures. The maximum number of trucks used was 34 for Policy 6 and 36 for Policy 7, both for 40% land use rate. The minimum number of trucks used was 32 for Policy 6 and 33 for Policy 7 (50% land use rate). The total truck ownership cost was calculated as

$$Trk_{oc} = (n_{trk})(n_d)(T_{oc}) \qquad \text{(Equation 7.2)}$$

where,

$Trk_{oc}$ = Total truck ownership cost per season ($)

$n_{trk}$ = Maximum number of trucks used by a policy

$n_d$ = No. of workdays in a season = (5 days/week)(25 weeks/season) = 125 days

$T_{oc}$ = Ownership cost per Truck ($450/day)

The maximum number of trucks used by the system under a given policy goes up as the land use rate goes down. This was because as the land use rate goes down, the number of loads at each SSL goes down. This forces the system to move loads from SSLs that are further away from the plant. These additional SSLs have a higher truck requirement and this causes an increase in the maximum number of trucks needed.

Policy 6 uses fewer trucks than Policy 7 for the same land use rate. This was attributed to the fact that Policy 6, which was generated from Policy 1 had a smoother transition between one SSL to the next. That is, in Policy 1, the transition from one SSL to the next was closely matched to travel time, which reduced the variation in truck demand. The post processing operations performed on Policy 6 to reduce interSSL travel did not completely remove this property as the SSLs assigned to each loader did not change.

Policy 7, on the other hand, moved to the closest SSL in its own sector and in some of the transitions, truck requirements between SSLs were more varied.

**Table 7.7 Truck Ownership cost**

| Policy | Maximum No. of Trucks used | Truck Ownership cost per season ($) |
|---|---|---|
| Policy 6, 50% land use rate | 32 | 1,800,000 |
| Policy 6, 45% land use rate | 33 | 1,856,250 |
| Policy 6, 40% land use rate | 34 | 1,912,500 |
| Policy 7, 50% land use rate | 33 | 1,856,250 |
| Policy 7, 45% land use rate | 35 | 1,968,750 |
| Policy 7, 40% land use rate | 36 | 2,025,000 |

The other truck cost component is the cost to move loads from the SSL to the plant. This cost depends on the SSL used during a season, the number of loads at a SSL and the distance between the plant and the SSL. For this analysis, it was assumed that each truck can travel a distance of 6.43 km (4 miles) for every 3.785 liters (1 gallon) of Diesel fuel (Cundiff, 2007). At $0.74 per liter of diesel, the travel cost is given by $(0.74)(3.785)/(6.43) or $0.43 per km. Table 7.8 shows the total distance traveled by the trucks for each policy and their corresponding cost. The total distance traveled was calculated by

$$Trk_{fc} = 2(0.74)\left(\sum_{i=1}^{155} D_i L_i\right), \qquad \text{(Equation 7.3)}$$

where,

$D_i$ = Distance from the plant to SSL i (km),

$L_i$ = Total number of loads used from SSL i,

The one way travel distance from each SSL to the plant is given in Appendix A5, **Error! Reference source not found.**.

**Table 7.8 Truck Travel cost**

| Policy | Total Distance Traveled by the Trucks (km) | Truck travel cost per season ($) |
|---|---|---|
| Policy 6, 50% land use rate | 1,261,931 | 542,630 |
| Policy 6, 45% land use rate | 1,315,812 | 565,799 |
| Policy 6, 40% land use rate | 1,356,548 | 583,316 |
| Policy 7, 50% land use rate | 1,267,575 | 545,057 |
| Policy 7, 45% land use rate | 1,317,126 | 566,364 |
| Policy 7, 40% land use rate | 1,405,582 | 604,400 |

The truck travel component was minimal for Policy 6 at 50% land use rate and increased as the land use rate went down. Policy 7 had consistently higher truck travel cost compared to Policy 6 for the same land use rates. This was attributed to the differences in the SSLs used by Policy 7 vs. Policy 6

### *7.6.2 Loader Cost:*

The loader cost consists of two subcomponents, the capital cost of owning and operating the loaders and interSSL travel cost for the loaders. The order of travel by the loaders from one SSL to the next was compiled from Policies 6 and 7 to calculate the total interSSL travel by each loader during one season. The transportation industry currently charges $450 per day to move the loader, plus a mileage rate of $3 per km ($5 per mile) (Smith, 2007). Table 7.9 shows the loader's interSSL move distances and the corresponding cost for Policies 6 and 7. The total cost was calculated by

$$TL_{oc} = \left\{ \sum_{j=1}^{155} \sum_{i=1}^{155} S_{ij} x_{ij} \right\}(3) + \left\{ \sum_{i=1}^{155} x_{ij} \right\}(450) \text{, where} \qquad \text{(Equation 7.4)}$$

$TL_{oc}$ = Total Loader cost per season ($)

$x_{ij}$ = 1, if a loader moves from SSL i to SSL j.

= 0, otherwise

$S_{ij}$ = Distance between SSL i to SSL j

**Table 7.9 Loader move cost table**

| Policy | Total Distance Traveled by the Loaders (km) | No. of Moves in a Season | Loader move cost per season ($) |
|---|---|---|---|
| Policy 6, 50% land use rate | 2,409 | 105 | 54,477 |
| Policy 6, 45% land use rate | 2,613 | 120 | 61,840 |
| Policy 6, 40% land use rate | 2,807 | 125 | 64,672 |
| Policy 7, 50% land use rate | 1,394 | 105 | 51,432 |
| Policy 7, 45% land use rate | 1,389 | 115 | 55,916 |
| Policy 7, 40% land use rate | 1,499 | 119 | 58,046 |

Policy 7 had consistently lower loader move distances when compared to Policy 6 for a given land use rate. This was due to the fact that each loader in Policy 7 moved only within its own sector while a loader in Policy 6 was free to move through out the procurement region. Differences in Loader move cost (Policy 6 – Policy 7) were $3,045, $5,924, and $6,626 for 50%, 45%, and 40% land use rates.

The simulation model also calculated the total number of hours each loader operated during the season (Table 7.12 and Table 7.45). The cost to operate the loader was calculated to be $67.05 per hour (Appendix A7.2 and A7.3). Table 7.10 shows the total operating hours for Loaders 1 to 9 under Policies 6 and 7 in one season.

**Table 7.10 Loader operating cost**

| Policy | Total Loader Operating hours per season | Loader Operating cost per season ($) |
|---|---|---|
| Policy 6, 50% land use rate | 9,461 | 634,360 |
| Policy 6, 45% land use rate | 9,375 | 628,594 |
| Policy 6, 40% land use rate | 9,332 | 625,711 |
| Policy 7, 50% land use rate | 9,421 | 631,678 |
| Policy 7, 45% land use rate | 9,432 | 632,416 |
| Policy 7, 40% land use rate | 9,388 | 629,465 |

The total number of hours Loaders 1 to 9 operated remained nearly constant around 9,400 h per season. As the land use rate decreased, the number of loads at each SSL also decreased. This caused the loaders to move to the next SSL sooner. This, combined with the triangular distribution used to model loader loading times caused a slight decline in the total number of operating hours as the land use rate decreased.

### *7.6.3 Unloader Cost:*

The cost to operate the unloader was calculated to be $37.22 per hour (Appendix A7.4). Table 7.11 shows the unloader operating hours for one season. The Unloader operating cost was calculated using

$TUL_{oc} = (UL1_h + UL2_h + UL3_h)(UL_{oc})$, where (Equation 7.5)

$TUL_{oc}$ = Total Unloader operating cost per season ($)
$UL1_h$ = Total number of operating hours per season, Unloader 1 (h)
$UL2_h$ = Total number of operating hours per season, Unloader 2 (h)
$UL3_h$ = Total number of operating hours per season, Unloader 3 (h)
$UL_{oc}$ = Unloader operating cost per hour = $37.22/h

The total number of operating hours for the unloader remained almost constant across policies 6 and 7 with little variation due to changes in land use rate and the triangular distribution used in the simulation model.

**Table 7.11 Unloader operating cost**

| **Policy** | **Total Unloader Operating Hours per Season** | **Unloader Operating Cost per Season ($)** |
|---|---|---|
| Policy 6, 50% land use rate | 2,659 | 98,968 |
| Policy 6, 45% land use rate | 2,630 | 97,889 |
| Policy 6, 40% land use rate | 2,634 | 98,037 |
| Policy 7, 50% land use rate | 2,671 | 99,415 |
| Policy 7, 45% land use rate | 2,677 | 99,638 |
| Policy 7, 40% land use rate | 2,674 | 99,526 |

## *7.7 Total Delivered Cost of Feedstock:*

Table 7.12 shows the total delivery cost to the plant under Policies 6 and 7 with a land use rate of 50%, 45% and 40%. The total delivery cost was calculated as

$$TDC = Trk_{oc} + Trk_{fc} + TLC + TU_{oc}, \qquad \text{(Equation 7.6)}$$

Where,

TDC = Total Delivered cost per season,

$Trk_{oc}$ = Total truck ownership cost per season,

$Trk_{fc}$ = Total truck fuel cost per season,

$TL_{oc}$ = Total loader operating cost per season

$TU_{oc}$ = Total Unloader operating cost per season.

The total delivered cost per Mg was calculated by

$$TDC_{Mg} = TDC \,/\, ((D)(\sum_{i=1}^{155} L_i)), \qquad \text{(Equation 7.7)}$$

where,

TDC = Total Delivered cost per season,

D = Biomass per load (Dry) = 14.4 Mg

$L_i$ = No. of loads used from SSL i

**Table 7.12 Delivered cost (loading, hauling, unloading) at the plant**

| Policy | Total Delivery cost ($) | Delivery cost ($/Mg) |
|---|---|---|
| Policy 6, 50% land use rate | 3,130,436 | 14.68 |
| Policy 6, 45% land use rate | 3,210,373 | 15.20 |
| Policy 6, 40% land use rate | 3,284,236 | 15.61 |
| Policy 7, 50% land use rate | 3,183,832 | 14.99 |
| Policy 7, 45% land use rate | 3,323,084 | 15.65 |
| Policy 7, 40% land use rate | 3,416,437 | 16.14 |

The lowest delivery cost was \$14.68, \$15.20, and \$15.61 per Mg under Policy 6 for 50%, 45% and 40% land use rates, respectively (Table 7.12). Policy 6 had consistently lower delivered cost across all land use rates. This was due to the lower truck requirement for the transportation system under Policy 6 when compared to Policy 7.

## *7.8 Results and Discussion*

Although Policy 7 had lower interSSL travel distances than Policy 6, the decrease in loader transport cost was not large enough to offset the cost of having additional trucks in the system. With each additional truck, \$56,250 is added to the final cost, Policy 7 will become competitive only when the reduction in interSSL travel becomes larger than 18750 km. With a normal interSSL travel distances of less than 2000 km per season, Policy 7 will not break even with Policy 6. It was concluded that Policy 6 was a better economic policy than Policy 7, and therefore the plant is recommended to use this strategy.

The truck ownership cost constitutes 57 to 60% of the total biomass delivery cost to the plant and is the largest contributor to the delivered cost (Table 7.13). The number of trucks needed for the system is inversely related to the land use rate. To decrease the truck ownership cost, the plant should actively look at increasing the number of loads available at SSLs, select more biomass closer to the plant by increasing the land use rates. The plant should also consider operating the trucks for longer hours and increase the number of loads the trucks transport to the plant on any given day. The truck system can either go to a 24/7 operation or use weekends to move the loads.

Loaders are still the most expensive components in the system and the second highest contributor to the total biomass delivery cost. Although there are only nine loaders in this system, the cost of operating one loader per season is much higher than the cost to own and operate an individual truck. Given a choice between lowering the same number of trucks or the number of loaders, the plant should consider the option with fewer loaders.

The part-time loader used in the system is both an opportunity and a problem. While it does provide additional capacity if the transportation system has a breakdown, or becomes incapable of supplying the requisite number of loads, it also adds to the final cost.

**Table 7.13 Delivered cost per Mg (loading, hauling, unloading) at the plant**

| Policy | Truck Ownership Cost $/Mg | Truck Travel Cost $/Mg | Loader Move Cost $/Mg | Loader Operating Cost $/Mg | Unloader Operating Cost $/Mg |
|---|---|---|---|---|---|
| Policy 6, 50% land use rate | 8.44 | 2.55 | 0.26 | 2.98 | 0.46 |
| Policy 6, 45% land use rate | 8.79 | 2.68 | 0.30 | 2.98 | 0.46 |
| Policy 6, 40% land use rate | 9.09 | 2.77 | 0.31 | 2.97 | 0.47 |
| Policy 7, 50% land use rate | 8.74 | 2.57 | 0.25 | 2.98 | 0.47 |
| Policy 7, 45% land use rate | 9.27 | 2.67 | 0.27 | 2.98 | 0.47 |
| Policy 7, 40% land use rate | 9.57 | 2.86 | 0.28 | 2.97 | 0.47 |

The third largest contributor to the cost was truck travel cost. For a given set of SSLs, the truck travel cost would not show much variation. Again, the only option for the plant to reduce this cost component is to increase the number of loads available to it from the SSLs closest to the plant.

The interSSL travel cost was 0.12% to 0.25% of the delivered cost and not a major contributor to the final delivery cost as expected. But the cost to hire a moving crew for the loader was a significant factor as the number of SSLs serviced during a season was over 100 for all policies. One way to reduce this component is to use SSLs that have larger number of loads. This will decrease the total number of moves during a season and reduce the move cost.

The unloaders in the system operated without much problem. The queue was used more frequently on days with higher load deliveries and dropped to low values during days with lower deliveries. Although the system requires three unloaders, if the plant moves to a 24/7 operation or transports loads on the weekends (6AM – 6PM), the number of unloaders can potentially be reduced to two.

# Chapter 8 – Summary and Recommended Future Research

## *8.1 Summary*

The primary goal of this study was to design a biomass logistics system and management strategies that would deliver the required number of loads each week to a bioprocessing plant with minimal cost. The transportation system consisted of a set of loaders, trucks and unloaders. Bales of biomass are placed into special temporary storage locations called Secondary Storage Locations or SSLs. Each SSL has a procurement radius of 3.2 km and it is assumed that a percentage (40, 45 and 50) of pasture land in that procurement region would be planted with biomass.

The transportation system of a cotton gin was modeled and studied with the current management policy (FIFO) followed by the gin to understand a logistic system where the processing plant (gin) pays for the transportation of the feedstock. The gin operated for 80 days per season with three breaks in operation due to non-availability of cotton modules. Two alternate management policies ("smallest first" and "longest first, smallest next") for transporting cotton modules were modeled and the superiority of such policies over the existing policy was demonstrated. The "smallest first" policy reduced the ginning season from 80 days to 61 days while the "longest first, smallest next" policy reduced the ginning season to 51 days.

GIS based raster analysis was used to generate the feedstock dataset for a seven-county region in southern piedmont region of Virginia (SPV). One hundred and fifty-five SSLs were placed in the SPV region. The total land area classified as pasture by National Land use Classification Data (NLCD) was determined for each of the individual SSL procurement regions. This information was then used to calculate the number of loads available at each of those locations based on a land use rate (40, 45, and 50%) and expected biomass yield (9 Mg/ha).

Tiger® road network for the SPV region was used to construct travel time cost rasters for the SSLs. These data were used to determine an optimal minimal travel time location for the plant in the seven-county region. Travel time and travel distances from the plant to each SSL were determined using Utility Network tool in ArcMap®. This data was then used to establish scheduling policies for the SSLs.

In this system, each SSL is unloaded once every six months. To unload an SSL, the loader loads 32 round bales (1.5 m diameter) onto a truck. The trucks then travel to the plant and an unloader unloads the trucks and places the load into the plant processing queue. The truck then returns to the loader for the next load. The load times was fixed at 0.5 h and unload time at 0.167 h. Once a loader has loaded all the bales at a SSL, it moves to the next SSL. When the loader moves from one SSL to the next during a work day, it loses the loading capability for that day. Analysis showed that it takes nine loaders to satisfy plant demand. All policies were analyzed with nine loaders operating through the season.

The number of trucks needed to keep the loader busy at a given SSL is a function of travel time to the plant from a particular SSL. The total number of trucks that the system needs on any given day varied depending on which SSLs were being unloaded on that day. The largest contributor to the total biomass delivery cost was truck ownership cost. Any system designed to minimize total system cost needs to minimize the total number of trucks used during a season. The number of trucks used by the system depends on the order in which the SSLs are unloaded. By varying the order of SSLs visited by the loaders, the maximum number of trucks needed could be controlled. Two policies, Policy 1 (STT-LTT-C) and Policy 2 (STT-LTT-WC), were initially considered to generate the loader schedule to reduce the maximum number of trucks used.

### *8.1.1 Scheduling Policy:*

Seven different scheduling policies (strategies) were studied. The two key variables were maximum trucks required and the maximum at-plant inventory during a season. The policies were management plans that the bioprocessing plant might follow in scheduling deliveries of raw material. The "optimum" plan was defined as the plan that minimizes at-plant inventory and simultaneously requiring the smallest number of trucks.

In Policy 1, all nine loaders were divided into two sets, with Loaders 1 to 4 in one set and Loaders 5 to 9 in the next. All the loaders in the first set followed a Shortest Travel Time (STT) schedule. That is, SSLs were assigned to these loaders such that Loader 1 had all SSLs that were close to the plant. When Loader 1's schedule was full, Loader 2 was filled in the same order. The loaders in the second set followed a Longest Travel Time (LTT) schedule. That is, SSLs were assigned to these loaders such that Loader 5 had SSLs that had the highest travel time from the SSL to the plant. When Loader 5's schedule was full, Loader 6 was assigned in the same order. This produced two sets of loaders, with each set having either an increasing truck requirement or a decreasing truck requirement through the season.

By combining these two sets, the maximum number of trucks used by the system was averaged. Policy 1 produced a schedule with a maximum truck requirement of 32 with an average truck requirement of 31 (50% land use rate). Although the truck requirement was minimized, the policy caused excess inventory at the plant and large amount of crisscrossing between SSLs during loader moves between SSLs. This resulted in a high cost to move loaders between SSLs.

Policy 2 followed a similar approach for assigning loaders to SSLs, except that the order in which the SSLs were allocated to a loader in the sets was changed. Instead of allocating the first group of SSLs to Loader 1, the first SSL was allocated to Loader 1, the second SSL was allocated to Loader 2, the third to Loader 3, the fourth to Loader 4. The fifth SSL was allocated to Loader 1 and so on until all the loaders in the set were filled. The LTT set also followed the same process, but in reverse order. This policy produced a schedule with a maximum truck requirement of 36 and an average truck requirement of 31 for 50% land use rate. Since the final truck ownership cost depended on the maximum number of trucks used and not on the average, Policy 2 was dropped from further analysis.

Policy 3 (STT-LTT-C-HL) was formulated to address the excess at-plant inventory produced by Policy 1. Loader 5 from Policy 1, which had the SSLs with highest travel time and consequently the highest truck requirement, was modified such that it operated every other week. The SSLs with highest travel times within this loader's schedule were dropped to account for the reduction in operating weeks. This policy produced a schedule with a maximum truck requirement of 32 and an average truck requirement of 29 for 50% land use rate. The maximum inventory level at the plant was reduced to 414 loads from the 1,236 loads achieved using Policy 1. The average at-plant inventory was reduced to 294 loads from 732 loads. An at-plant inventory of 294 loads corresponded to less than three days worth of transport and was deemed satisfactory.

Policy 4 (STT-LTT-C-MLT) was formulated to reduce loader crisscrossing during interSSL moves. InterSSL travel distances were calculated based on Euclidian distances between SSLs and a road tortuosity factor (road winding factor). The tortuosity factor was calculated by dividing the actual road travel distance from a SSL to the plant by the Euclidian distance from that SSL to the plant. The average tortusoity factor for all 155 SSLs was 1.3. Policy 1's schedule was run through a Concorde, a Traveling Salesman Problem solver, to generate optimal Hamiltonian cycles for each loader (Appendix A6). This additional step caused the LTT-STT rule within a given loader to be broken, but produced a schedule that had a maximum truck requirement of 32 with an average truck requirement of 31 for 50% land use rate, matching the results from Policy 1. Since the part-time loader concept was not implemented, Policy 4 still had the same high at-plant inventory issue as Policy 1.

Policy 5 (Sector based loader assignment) divided the entire SPV region into five sectors. Sectors 1 to 4 had two loaders each, and Sector 5 had one loader. One loader from Sectors 1 to 4 started close to the plant and returned to the same location at the end of the season. The other loader started from the SSL with the highest travel time within the sector and visited the SSLs that were close to it. Loader 9, which was the only loader in Sector 5, visited all the SSLs in its sector starting from the SSL closest to the plant. The

SSLs within each loader's schedule was run through Concorde to generate optimal Hamiltonian cycles to minimize interSSL travel. This policy produced a schedule with a maximum truck requirement of 34 with an average truck requirement of 31 for 50% land use rate. Policy 5 also produced excessive at-plant inventory. The maximum at-plant inventory stood at 1,206 loads with an average of 693 loads.

Policy 6 (STT-LTT-HL-MLT) was formulated by combining the part-time loader concept from Policy 3 and minimal loader travel concept from Policy 4. The loader schedule from Policy 3 was run through Concorde and optimal Hamiltonian cycles for loader moves generated. This policy produced a schedule with a maximum truck requirement of 32, with an average truck requirement of 29 for 50% land use rate. The maximum at-plant inventory was 459 loads, with an average of 302 loads.

Policy 7 (Sector based loader assignment with half loader) was formulated by combining the part-time loader concept from Policy 3 and sector based loader assignment of Policy 5. Loader 9 was selected for conversion to part-time loader, as it had the widest variation in SSL travel times. Dropping the SSLs with high travel times would convert Loader 9's SSL schedule to one with low truck requirement. This reduced the total truck requirement and produced a schedule with a maximum truck requirement of 33, with an average truck requirement of 29 at 50% land use rate. This was the only policy in which a half loader reduced the maximum number of trucks required during a season.

### *8.1.2 Discrete Event Simulation:*

A discrete event simulation model for the logistic system was constructed in Arena®, and the schedule generated by Policies 6 and 7 was simulated to validate the policies and to generate the productive operating times for loaders, trucks, and unloaders. The comparison of operating hours in this paragraph is for 50% land use rate. The loaders operated for 9,461 hours using Policy 6 and for 9,421 hours using Policy 7. The operating cost of the loaders over a 6-month season was estimated at $634,360 and $631,678 using Policies 6 and 7, respectively. The unloaders operated for a total of 2,659 and 2,671 hours using policies 6 and 7, respectively. The unloader operating cost over a 6-month season was estimated at $98,968 and $99,415 for policies 6 and 7, respectively. The truck cost averaged $8.44/Mg and $8.74/Mg for Policies 6 and 7, respectively (Truck cost was computed based on the maximum number of trucks per season). The total biomass delivery cost was $14.68 and $14.99 per Mg for Policies 6 and 7 respectively. Based on the study, Policy 6 is recommended over all other policies.

The simulation model was used to check the sensitivity of the system to variations in land use rate, truck travel times, and plant processing times. Decreasing the land use rate from 50% to 40% increased the number of SSLs needed from 105 to 125. The delivered cost ($/Mg) increased by $0.93, from $14.68 to $15.61, an increase of 6.3% . The travel times were changed from a constant value to a triangular distribution with the minimum value set to -10% of original Travel time, maximum value set to 110% of original Travel time and the mode set to original Travel time. There was little change in the system behavior.

The travel time distribution was then changed to a triangular distribution with the minimum value set to -10% of original Travel time, maximum value set to 120% of original Travel time and the mode set to original Travel time. The system still performed without any problems. It showed that the logistic system was immune to small changes in travel time. This was due to the fact that a truck typically waited at an SSL to be loaded. Any increase in travel time was offset by decrease in the truck waiting times at the SSL, thus truck loads-per-day did not decrease.

The model was run with the processing time for each load reduced from 17.14 min to 17 min. The plant, when operating on the Policy 6 schedule, ran out of inventory three times. The plant ran out of inventory five times when operating under Policy 7 schedule. The plant stopped more often using Policy 7, since there were a larger number of days in Policy 7 where the at-plant inventory level was low.

## 8.2 Rules for generating a minimal cost logistic system

The following section describes the general rules for generating a minimal cost biomass logistic system based on the study.

### 8.2.1 Rule 1 – Optimal plant Location

The location of the facility is probably the most important factor in generating minimum delivered cost. The location of the plant determines the travel time to SSLs and thereby determines the number of trucks each SSL requires during a season. For a given set of SSLs, the plant location further determines the lower bound for the maximum number of trucks needed. A minimum travel cost optimization model was used in this analysis (Refer to Chapter 5). This technique is recommended as the location generated will minimize the maximum number of trucks needed in a procurement region.

### 8.2.2 Rule 2 – STT-LTT assignment

The Shortest Travel Time – Longest Travel Time (STT-LTT) rule should be used to assign loaders to SSLs as it produced schedules with minimum variation in truck requirement. As long as the SSLs are not swapped between loaders, the positive effects of this rule will remain, as demonstrated in Policies 4 and 6.

### 8.2.3 Rule 3 – SSL Selection

Selecting a SSL to drop from the schedule should be based on the truck requirement to haul from that SSL and the location of the SSL in a loader's schedule. Preference should be given to SSLs with a high truck requirement when dropping SSLs from a loader's schedule. Once dropped, the loader schedule must be regenerated with the maximum total truck requirement as a constraint.

### 8.2.4 Rule 4 – Truck Load Times

The system design should minimize the truck load times. In the current system, each loading operation adds 30 min to the cycle length. The truck load times constitutes 21% of truck cycle times. Reducing the cycle time allows an individual truck to make more trips per day and this reduces the total truck requirement. The load times can be reduced by using more efficient loading machinery. The unload times in the system, was already at a practical minimum of 10 min.

### *8.2.5 Rule 5 – Minimal At-plant Inventory*

The system should maintain the at-plant inventory above zero during a season. Although the present cost analysis did not include an at-plant inventory storage cost, in an actual plant, there will be cost associated with developing storage area. A safety stock in storage would reduce the effect of variations in system performance. The additional cost associated with the safety stock must be balanced against the penalty cost associated with stopping and restarting the bioprocessing plant.

## *8.3 Recommended Future Research:*

As stated in earlier chapters, the transportation system needs to supply 117 loads per day during the work week for the plant for uninterrupted operation. With each loader capable of supplying 15 loads per day, a transportation system with 8 loaders (a theoretical maximum of 120 loads combined) was needed. Policies 1 to 7 showed that a transportation system with 8 loaders would not be able to supply the required number of loads as some loading days are lost when the loader moves from one SSL to next during the workweek. This forced the transportation system to use 9 loaders. With 9 loaders, the system overcompensated and supplied more than required number of loads, leading to a buildup of excess inventory at the plant. Policies 3, 6 and 7 addressed the problem of excess inventory by mandating that the 9$^{th}$ loader only operate every other week.

Another way to reduce this inventory buildup is to schedule the loaders such that all moves take place during weekends, thereby reducing the number of loaders and trucks needed. The major issue with modeling the present system is that move operations, when they occur during the weekend, effectively decreases the total time a loader spends in a location. That is, consider two SSLs, A and B with 9 or 10 days worth of loads, respectively. If the initial processing starts on a Monday, both SSLs will take 10 working days to process. On the other hand, if the processing starts on a Tuesday, then SSL A will take 9 working days to process and SSL B will need 11 days.

If the logistics system can be designed whereby the loads are prepared during the 10 h workdays (bales are loaded into frames) for trucks to pick them, the trucks need not wait at the SSLs. Load times can, theoretically, be reduced to 0.167 h.

An even larger benefit can be obtained if trucks can haul 24 h/day. Loaded containers are loaded onto a truck by the truck drivers. All that is required is a suitable forklift parked at the SSL. Containers loaded at one SSL will be hauled during the day and containers at a second SSL will be hauling during the evening. Potentially, the number of trucks needed could be reduced by 50%. Since truck cost is  % of total delivered cost, this is a significant advantage. It is noted that a reduction in truck cost will be partially offset by the ownership and maintenance cost of the containers. Future research will define the amount that can be invested in containers to reduce truck cost.

The data could be modified by splitting all SSLs into sub-locations with each sub-location having exactly one day's worth of load. An extra dummy day/sub-location could be added to each SSL to account for the productivity loss when the loader moves to the next SSL. An additional dummy day/sub-location can also be added for every five work days to account for the variations introduced in SSL service length. Consider SSL A from the previous example. It would be split into 9 sub-locations and 2 dummy sub-locations. SSL B, on the other hand, would have 10 sub-locations and 3 dummy sub-locations. By dividing each SSL into sub-locations, the mathematical model would be able to determine a schedule on a daily basis and satisfy the supply constraint of 117 loads per day.

The current system places an additional constraint that the loader will not move to the next SSL until all loads assigned to that loader from that SSL are loaded. To address this constraint, the interSSL distance matrix should be modified so that a loader can only enter one sub-location and move to another sub-location in the SSL chain. The only exception would be SSLs with loads that are exact multiples of 5. In this case, the loader can move to the next sub-location from any of the two dummy sub-locations. The loader can only move to the next SSL sub-location chain from the last dummy sub-location.

The mathematical model adds a penalty cost for every dummy location assigned to a loader during a workday. This would force the model to strive for a solution where all dummy locations are assigned to the 6$^{th}$ day of the week, Saturday. The extra dummy sub-location after every 5$^{th}$ workday will take the extra work day that may be scheduled on a Saturday.

The interSSL distance matrixes with sub-locations should be modified by adding small additional costs so that cycling is eliminated. The problem could then be solved as a multiple TSP with unknown number of cities to generate the schedule.

References:


Alvim, A.C.F., Ribeiro, C.C., Glover, F., Aloise, D.J., 2004. A Hybrid Improvement Heuristic for the One-Dimensional Bin Packing Problem. *Journal of Heuristics*, 10, 205-229.

Applegate, D., 1998. On the Solution of Traveling Salesman Problems. Forschungsinst. für Diskrete Mathematik; Rheinische Friedrich-Wilhelms-Univ.

Applegate, D., Bixby, R., Chvatal, V., Cook, W., 2001. TSP cuts which do not conform to the template paradigm. *Computational Combinatorial Optimization*, 261–303.

Baita, F., Pesenti, R., Ukovich, W., Favaretto, D., 2000. A comparison of different solution approaches to the vehicle scheduling problem in a practical case. *Computers and Operations Research*, 27, 1249-1269.

Banks, J., Carson, J.S., 2001. Discrete-event system simulation. Prentice Hall Upper Saddle River, NJ.

Barbarosoglu, G., Ozgur, D., 1999. A tabu search algorithm for the vehicle routing problem. *Computers and Operations Research*, 26, 255-270.

Bazaraa, M.S., Jarvis, J.J., Sherali, H.D., 1990. Linear programming and network flows. John Wiley & Sons, Inc. New York, NY, USA.

Bell Laboratories, 2003. AMPL Student Edition, Version No. 20030527.

Bellmore, M., Nemhauser, G.L., 1968. The Traveling Salesman Problem: A Survey. *Operations Research*, 16, 538-558.

Bixby, R.E., Lee, E.K., 1998. Solving a Truck Dispatching Scheduling Problem Using Branch-and-Cut. *Operations Research*, 46, 355-367.

Black, P.E., 2005. Dictionary of Algorithms and Data Structures. *National Institute of Standards and Technology web site. Retrieved April*, 23, 2005.

Brunback, C.T., L.S. Marsh, J.S. Cundiff, 1995. Compositional change in large round switchgrass bales stored in Virginia.

Burkard, R.E., Deineko, V.G., 1995. Polynomially solvable cases of the traveling salesman problem and a new exponential neighborhood. *Computing*, 54, 191-211.
Carino, H.F., Willis, D.B., 2001a. Enhancing the profitability of a vertically integrated wood products production system. Part 1. A multistage modelling approach. *Forest products journal*, 51, 37-44.
Carino, H.F., Willis, D.B., 2001b. Enhancing the profitability of a vertically integrated wood products production system. Part 2. A case study. *Forest products journal*, 51, 45-53.
Chan, F.T.S., Au, K.C., Chan, P.L.Y., 2005. A genetic algorithm approach to bin packing in an ion plating cell. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 219, 1-13.
Christofides, N., 1985. Vehicle routing. *The Traveling Salesman Problem: A Guided Tour of Combinatorial Optimization*, 431-448.
Clochard, J.M., Naddef, D., 1993. Using path inequalities in a branch and cut code for the symmetric traveling salesman problem. *Rinaldi, Giovanni (ed.) et al., Integer programming and combinatorial optimization. Proceedings of a conference held at Centro Ettore Majorana, Erice, Italy, April 29-May 1*, 29.
Coffman Jr, E.G., Garey, M.R., Johnson, D.S., 1996. Approximation algorithms for bin packing: a survey. *Approximation algorithms for NP-hard problems table of contents*, 46-93.
Cormen, T.H., 2001. Introduction to Algorithms. MIT Press.
Cundiff, J., 2007. Economic Analysis of two Receiving Facility Designs for a Bioenergy Plant. 2007 Annual International Meeting. ASABE, Minneapolis, Minnesota
Cundiff, J.S., Grisso, R., Ravula, P.P., 2004. Management System for Biomass Delivery at a Conversion Plant ASAE/CSAE meeting paper, Ontario, Canada.
Cundiff, J.S., Marsh, L.S., 1996. Harvest and storage costs for bales of switchgrass in the southeastern United States. *Bioresource Technology*, 56, 95-101.
Custom Simulations, 2004. Sigma for Windows, 1178 Laurel St, Berkeley, CA.
Dantzig, G., Fulkerson, R., Johnson, S., 1954. Solution of a Large-Scale Traveling-Salesman Problem. *Journal of the Operations Research Society of America*, 2, 393-410.
De Mol, R.M., Jogems, M.A.H., Van Beek, P., Gigler, J.K., 1997. Simulation and optimization of the logistics of biomass fuel collection. *Netherlands Journal of Agricultural Science*, 45, 217–226.
Department of Energy, 2003. Roadmap for Agriculture Biomass Feedstock Supply in the United States. Defense Technical Information Center, Washington, D. C.
Department of Energy, 2006. Annual Energy Review 2005. Office of Energy Markets and End Use, Energy Information Administration,U.S. Department of Energy, Washington, DC 20585.
Department of Energy, 2006. U.S. Primary Energy Consumption by Source and Sector. Office of Energy Markets and End Use, Energy Information Administration,U.S. Department of Energy
Department of Energy, U.S., 2007. Large Purchasers of Green Power. in: http://www.eere.energy.gov/greenpower/buying/customers.shtml?page=1&companyid=250 (Ed.).

Dias, N.P., 1995. Linear programming approach for designing a herbaceous biomass delivery system Industrial and systems Engineering Department. Virginia Tech, Blacksburg.

Downing, M., Graham, R.L., 1993. Evaluating a biomass resource: The TVA region-wide biomass resource assessment model. *Conference: 1. biomass conference of the Americas: energy, environment, agriculture, and industry, Burlington, VT (United States), 30 Aug-2 Sep 1993*.

Drezner, Z., Hamacher, H.W., 2002. Facility Location: Applications and Theory. Springer.

Du Staff, D.Z., Du, D., Pardalos, P.M., 1998. Handbook of Combinatorial Optimization. Kluwer Academic Publishers.

ESRI, 2000. Census Tiger® 2000's road and rail data www.ESRI.com/data/download/census_2000tigerline/index.html, Accessed on: June 2004.

ESRI, 2005. ArcCatalog and ArcMap, Version 8.1, ESRI, 380 New York Street, Redlands, CA 92373-8100.

Ferrell, J.E., Wright, L.L., Tuskan, G.A., 1995. Research to develop improved production methods for woody and herbaceous biomass crops. *2. meeting on biomass of the Americas, Portland, OR (United States), 21-24 Aug 1995*.

Gallis, C., 2002. Simulation of forest products export logistics: A newsprint paper case study. *Forest products journal*, 52, 19-24.

Gendreau, M., Hertz, A., Laporte, G., 1994. A Tabu Search Heuristic for the Vehicle Routing Problem. *Management Science*, 40, 1276-1290.

Graham, R.L., Liu, W., Downing, M., Noon, C.E., Daly, M., Moore, A., 1997. The effect of location and facility demand on the marginal cost of delivered wood chips from energy crops: A case study of the State of Tennessee. *Biomass and Bioenergy*, 13, 117-123.

Graham, R.L., Liu, W., Jager, H.I., English, B.C., Noon, C.E., Daly, M.J., 1996. A regional-scale GIS-based modeling system for evaluating the potential costs and supplies of biomass from biomass crops. *Proceedings of the 9th European Bioenergy Conference, Copenhagen (DK), 06/24/1996--06/27/1996*.

Greene, N., 2004. Growing energy. How biofuels can help end America's oil dependence. *Natural Resources Defense Council*, vii+86pp.

Gutin, G., Punnen, A.P., 2002. The Traveling Salesman Problem and Its Variations. Kluwer.

Hameri, A.P., Lehtonen, J.M., 2001. Production and supply management strategies in Nordic paper mills. *Scandinavian Journal of Management*, 17, 379-396.

Husdal, J., 2000. How to make a straight line square - Network analysis in raster GIS GIS. University of Leicester.

ILOG, 2004. CPLEX. Student Edition, Version 9.1 ed.

Khanna, S., Motwani, R., Sudan, M., Vazirani, U., 1998. On Syntactic versus Computational Views of Approximability. *SIAM Journal on Computing*, 28, 164-191.

Law, A.M., Kelton, W.D., 2000. Simulation Modeling and Analysis. 2nd ed. McGraw-Hill Higher Education.

Lehtonen, J.M., Holmstrm, J., 1998. Is just-in-time applicable in paper industry logistics? *Supply Chain Management: An International Journal*, 3, 21-32.
McLaughlin, S., Bouton, J., Bransby, D., Conger, B., Ocumpaugh, W., Parrish, D., Taliaferro, C., Vogel, K., Wullschleger, S., 1999. Developing switchgrass as a bioenergy crop. *Perspectives on new crops and new uses. ASHS Press, Alexandria, VA*, 282–299.
McLaughlin, S.B., 1992. New switchgrass biofuels research program for the Southeast. *Conference: Annual automotive development technology contractorscoordination meeting, Dearborn, MI (United States), 2-5 Nov 1992*.
Moscato, P., 1998. TSPBIB Home Page. http://www.ing.unlp.edu.ar/cetad/mos/TSPBIB_home.html, Accessed November 12th 2006.
Moser, W.H., 1994. Movable floor mechanism. in: U.S.P.a.T. Office (Ed.). US Patent 5,316,133.
Nilsson, D., 1999a. SHAM-a simulation model for designing straw fuel delivery systems. Part 1: model description. *Biomass and Bioenergy*, 16, 25-38.
Nilsson, D., 1999b. SHAM-a simulation model for designing straw fuel delivery systems. Part 2: model applications. *Biomass and Bioenergy*, 16, 39-50.
Noon, C.E., 1993. TVA GIS-based biomass resource assessment. Vol. I. *Proceedings of the First Biomass Conference of the Americas. National Renewable Energy Laboratory, Golden CO*, 74-78.
Noon, C.E., Daly, M.J., 1996. GIS-based biomass resource assessment with bravo. *Biomass and Bioenergy*, 10, 101-109.
Noon, C.E., Daly, M.J., Graham, R.L., Zahn, F.B., 1996b. Transportation and Site Location Analysis for Regional Integrated Biomass Assessment (RIBA). *Proceeding of the Seventh National Bioenergy Conference, Nashville, TN (US), 09/15/1996--09/20/1996*.
Papadimitriou, C.H., Steiglitz, K., 1998. Combinatorial Optimization: Algorithms and Complexity. Dover Publications.
Parrish, D.J., Wolf, D.D., and Daniels, W.L., 1993. Switchgrass as a biofuels crop for the upper southeast: variety trials and cultural improvements 1993 Annual report. Oak Ridge National laboratory.
Priepke, E.H., 2007. Personal communication. CNH America LLC, PO Box 1895, MS 640, New Holland, PA 17557-0903.
Rego, C., 1998. A Subpath Ejection Method for the Vehicle Routing Problem. *Management Science*, 44, 1447-1459.
Rockwell Software, 2002. Arena Version 7.1. Building 2, 2000 Marconi Drive, Warrendale, PA 15086 USA.
Roe, B., Teisl, M.F., Levy, A., Russell, M., 2001. US consumers' willingness to pay for green electricity. *Energy Policy*, 29, 917-925.
Scholl, A., Klein, R., Jurgens, C., 1997. BISON: a fast hybrid procedure for exactly solving the one-dimensional bin packing problem. *Computers and Operations Research*, 24, 627-645.
Sladden, S.E., Bransby, D.I., Aiken, G.E., 1991. Biomass yield, composition and production costs for eight switchgrass varieties in Alabama. *Biomass and Bioenergy*, 1, 119-122.

Smith, L.N., 2007. Personal communication. L.N. Smith Construction, Blacksburg, VA.
Sokhansanj, S., Turhollow, A., Cushman, J., Cundiff, J., 2002. Engineering aspects of collecting corn stover for bioenergy. *Biomass and Bioenergy*, 23, 347-355.
Syam, S.S., 2002. A model and methodologies for the location problem with logistical components. *Computers and Operations Research*, 29, 1173-1193.
Tembo, G., Epplin, F.M., Huhnke, R.L., 2003. Integrative investment appraisal of a lignocellulosic biomass-to-ethanol industry. *Journal of Agricultural and Resource Economics*, 28, 611-633.
US Census Bureau, 2000. UA Census 2000 TIGER/Line® Files Technical Documentation. http://www.census.gov/geo/www/tiger/tigerua/ua2ktgr.pdf pp 3-28 to pp 3-31. Accessed on: June 2004.
USGS, 2000. National land-use classification data (NLCD), USGS seamless data server. http://nmviewogc.cr.usgs.gov/viewer.htm/ , Accessed on: June 2004. .
Virginia Tech, 1990. Cartographic county boundary shapes for Virginia, . ftp://gis-server.lib.vt.edu/census80-90/CENBEND_VA/CENBND90/COUNTY/. Accessed on: June 2004.
Wu, T.H., Low, C., Bai, J.W., 2002. Heuristic solutions to multi-depot location-routing problems. *Computers and Operations Research*, 29, 1393-1415.
Zhan, F.B., Chen, X.W., Noon, C.E., Wu, G.Y., 2005. A GIS-enabled comparison of fixed and discriminatory pricing strategies for potential switchgrass-to-ethanol conversion facilities in Alabama. *Biomass and Bioenergy*, 28, 295-306.

# Appendix A5 – GIS Data Generation

**Table A5. 1 SPV SSL Coordinates**

| SSL Id | POINT_X (m) | POINT_Y (m) |
|---|---|---|
| 1 | 662269.57170700000 | 4049919.91202999000 |
| 2 | 605284.00131600000 | 4097648.63692000000 |
| 3 | 639067.09817699900 | 4152081.91045999000 |
| 4 | 613301.95064399900 | 4137834.95066000000 |
| 5 | 672520.48208800000 | 4113429.43709000000 |
| 6 | 711803.13993299900 | 4071297.61151999000 |
| 7 | 678042.06992699900 | 4065772.76209999000 |
| 8 | 611833.77217699900 | 4109440.50915999000 |
| 9 | 699621.92909600000 | 4052387.93212000000 |
| 10 | 623424.41806699900 | 4111335.87227000000 |
| 11 | 635871.23783700000 | 4147214.75597999000 |
| 12 | 633023.21055099900 | 4141765.12024000000 |
| 13 | 632747.78282099900 | 4135380.65408999000 |
| 14 | 624524.84602499900 | 4139232.34887999000 |
| 15 | 617200.93929100000 | 4144032.66054000000 |
| 16 | 619433.49745599900 | 4135006.72689000000 |
| 17 | 626092.41705599900 | 4134408.68934000000 |
| 18 | 622004.45518199900 | 4129703.21645000000 |
| 19 | 628404.20924999900 | 4127439.73182999000 |
| 20 | 609529.94731800000 | 4125548.73437999000 |
| 21 | 615801.09592899900 | 4123418.69789000000 |
| 22 | 622211.87548000000 | 4122430.39513000000 |
| 23 | 628014.81169899900 | 4121015.95080000000 |
| 24 | 632052.77221099900 | 4124127.65143000000 |
| 25 | 638594.51252800000 | 4126570.78904000000 |
| 26 | 638374.46079899900 | 4133286.60789000000 |
| 27 | 643411.54683300000 | 4129585.02130000000 |
| 28 | 649916.27679499900 | 4130136.25918000000 |
| 29 | 643244.61772500000 | 4137433.82843999000 |
| 30 | 648251.23844700000 | 4133972.36209000000 |
| 31 | 651439.77446400000 | 4138956.79493999000 |
| 32 | 647264.03417100000 | 4140576.47121000000 |
| 33 | 623231.01862600000 | 4116664.25418000000 |
| 34 | 629471.46870700000 | 4106468.94333000000 |
| 35 | 632225.21124199900 | 4111908.48591999000 |
| 36 | 639053.47755499900 | 4114657.33803000000 |
| 37 | 636712.75638000000 | 4119883.14318000000 |
| 38 | 641879.77877900000 | 4119912.29076999000 |
| 39 | 651199.14236199900 | 4117880.15070000000 |
| 40 | 645087.36177600000 | 4109679.08647000000 |
| 41 | 666973.21583100000 | 4127619.80977000000 |
| 42 | 664734.71146799900 | 4122165.81840000000 |
| 43 | 669828.45254199900 | 4119148.71400000000 |
| 44 | 669797.82246000000 | 4106657.27699999000 |

| SSL Id | POINT_X (m) | POINT_Y (m) |
|---|---|---|
| 45 | 655908.29411000000 | 4106716.46661000000 |
| 46 | 646400.88307600000 | 4102173.54105000000 |
| 47 | 640977.24233399900 | 4097128.11081000000 |
| 48 | 646219.01246999900 | 4097182.63705000000 |
| 49 | 606394.49664999900 | 4106328.66335000000 |
| 50 | 611452.67599899900 | 4094137.86047999000 |
| 51 | 618647.26109599900 | 4094620.57517000000 |
| 52 | 626177.94122299900 | 4091859.99731000000 |
| 53 | 632788.89278800000 | 4088455.47166999000 |
| 54 | 638801.59450699900 | 4090390.70854000000 |
| 55 | 645802.83102100000 | 4090303.67849999000 |
| 56 | 650443.05960599900 | 4093482.91925999000 |
| 57 | 655759.96953400000 | 4095519.60492999000 |
| 58 | 651795.13323599900 | 4101030.85582000000 |
| 59 | 658158.05390599900 | 4100322.09426000000 |
| 60 | 661963.90569299900 | 4094648.95130999000 |
| 61 | 651854.27184299900 | 4089577.69704000000 |
| 62 | 658273.27136899900 | 4089128.86977999000 |
| 63 | 669285.26196200000 | 4094109.66710000000 |
| 64 | 673396.65471200000 | 4093966.91638999000 |
| 65 | 641056.02946300000 | 4083910.69748000000 |
| 66 | 644563.82977299900 | 4074081.78390000000 |
| 67 | 647017.73208800000 | 4079474.57255000000 |
| 68 | 652184.59671099900 | 4081392.59510000000 |
| 69 | 657938.79929800000 | 4085202.52264000000 |
| 70 | 632510.61818800000 | 4077402.60546000000 |
| 71 | 638786.74141000000 | 4077858.96815000000 |
| 72 | 626031.12507600000 | 4075846.57583000000 |
| 73 | 619670.93585799900 | 4071652.72624999000 |
| 74 | 627468.86984900000 | 4066164.03812000000 |
| 75 | 633561.01743899900 | 4065271.41687999000 |
| 76 | 637737.06328500000 | 4061681.29838000000 |
| 77 | 631378.56370499900 | 4059342.48026000000 |
| 78 | 613539.16874600000 | 4082439.80216000000 |
| 79 | 610093.26434200000 | 4076980.05060000000 |
| 80 | 604056.12195199900 | 4073050.64692000000 |
| 81 | 606825.61676799900 | 4067231.33099000000 |
| 82 | 615129.89810100000 | 4061997.22215999000 |
| 83 | 616913.64155599900 | 4056978.30005999000 |
| 84 | 646959.36213200000 | 4066464.93545000000 |
| 85 | 652902.04835599900 | 4072750.14048000000 |
| 86 | 658992.33467799900 | 4075592.47702000000 |
| 87 | 667838.08405399900 | 4077965.85329000000 |
| 88 | 650181.62861899900 | 4060805.47878000000 |
| 89 | 658178.45482600000 | 4065491.36075000000 |
| 90 | 666797.34932899900 | 4069841.86466000000 |
| 91 | 672122.69800800000 | 4069064.00669999000 |

| SSL Id | POINT_X (m) | POINT_Y (m) |
|---|---|---|
| 92 | 662052.08838099900 | 4062230.74891000000 |
| 93 | 660015.48719200000 | 4056525.73369000000 |
| 94 | 667864.18955899900 | 4056119.94791000000 |
| 95 | 672500.75157800000 | 4052322.57865000000 |
| 96 | 656744.78822100000 | 4047807.10962999000 |
| 97 | 628453.34489099900 | 4082933.78886000000 |
| 98 | 636026.28519600000 | 4083546.44737000000 |
| 99 | 633349.72635000000 | 4071713.59711000000 |
| 100 | 639731.10386200000 | 4072612.92255999000 |
| 101 | 607473.88411300000 | 4090361.83336000000 |
| 102 | 603524.39031599900 | 4086881.89067000000 |
| 103 | 685457.23514999900 | 4118562.49226999000 |
| 104 | 690885.74474300000 | 4115711.05329000000 |
| 105 | 696669.91520699900 | 4118021.71823999000 |
| 106 | 701147.17327499900 | 4111245.79746000000 |
| 107 | 705858.27983500000 | 4115530.58258999000 |
| 108 | 710993.72929100000 | 4102602.42310999000 |
| 109 | 719016.82780400000 | 4108065.00312000000 |
| 110 | 724707.21112899900 | 4105002.57895000000 |
| 111 | 715283.61146399900 | 4082621.79758000000 |
| 112 | 696739.17676099900 | 4094150.90645000000 |
| 113 | 704354.93492499900 | 4086467.31479999000 |
| 114 | 710077.79328400000 | 4082618.61830000000 |
| 115 | 690032.76939999900 | 4085867.87793000000 |
| 116 | 692735.61782499900 | 4079947.50446000000 |
| 117 | 697868.87517699900 | 4078391.13914000000 |
| 118 | 676876.87882999900 | 4087017.49030000000 |
| 119 | 680801.75557200000 | 4083807.56791999000 |
| 120 | 685930.74137499900 | 4081182.60808000000 |
| 121 | 689230.56061599900 | 4076730.74990999000 |
| 122 | 691882.18771199900 | 4073447.61069000000 |
| 123 | 691944.76986500000 | 4067156.19258000000 |
| 124 | 691573.71059200000 | 4060031.01011000000 |
| 125 | 676248.13142999900 | 4097053.92877000000 |
| 126 | 678169.21212499900 | 4108228.55651000000 |
| 127 | 686556.57072800000 | 4106913.41063999000 |
| 128 | 693444.62235399900 | 4104880.70269000000 |
| 129 | 676723.79780700000 | 4130445.57351000000 |
| 130 | 699880.86715900000 | 4046384.20447999000 |
| 131 | 678485.66784999900 | 4054474.29926999000 |
| 132 | 674300.18910399900 | 4059039.85630000000 |
| 133 | 651283.63917200000 | 4052804.24917999000 |
| 134 | 600577.99779599900 | 4108784.76596000000 |
| 135 | 600762.34490300000 | 4104020.49824000000 |
| 136 | 595666.14095399900 | 4104515.63185000000 |
| 137 | 590167.27565700000 | 4100165.83486999000 |
| 138 | 583648.47142700000 | 4097159.17347999000 |

| SSL Id | POINT_X (m) | POINT_Y (m) |
|---|---|---|
| 139 | 595276.22552700000 | 4098161.72297000000 |
| 140 | 591620.55587399900 | 4091981.94921999000 |
| 141 | 581618.23727399900 | 4084692.49593000000 |
| 142 | 600290.62098600000 | 4088706.35299000000 |
| 143 | 609570.02735999900 | 4101360.85024000000 |
| 144 | 615921.16560800000 | 4103238.53377000000 |
| 145 | 600650.20362499900 | 4081670.90798000000 |
| 146 | 595970.41987700000 | 4076144.73808000000 |
| 147 | 583830.94545500000 | 4063868.01877000000 |
| 148 | 588626.02272799900 | 4059490.56976999000 |
| 149 | 587981.90909299900 | 4053046.20200000000 |
| 150 | 593870.56765500000 | 4054209.95912999000 |
| 151 | 601854.61353900000 | 4052271.79251000000 |
| 152 | 627546.32499999900 | 4052859.57347999000 |
| 153 | 712188.15246000000 | 4077043.63988000000 |
| 154 | 675709.56984899900 | 4074762.30204000000 |
| 155 | 678009.83581299900 | 4079078.95581999000 |

**Table A5. 2 SPV data, 50% land use rate**

| SSL ID | Cell count | AREA in Sq.Meters | Area in acres | Area Used in ha | Tons at 9Mg/ha |
|---|---|---|---|---|---|
| 1 | 10829 | 9746100 | 2408 | 487 | 4386 |
| 2 | 13030 | 11727000 | 2898 | 586 | 5277 |
| 3 | 12953 | 11657700 | 2881 | 583 | 5246 |
| 4 | 13141 | 11826900 | 2922 | 591 | 5322 |
| 5 | 14045 | 12640500 | 3124 | 632 | 5688 |
| 6 | 8037 | 7233300 | 1787 | 362 | 3255 |
| 7 | 9159 | 8243100 | 2037 | 412 | 3709 |
| 8 | 8733 | 7859700 | 1942 | 393 | 3537 |
| 9 | 8793 | 7913700 | 1956 | 396 | 3561 |
| 10 | 15374 | 13836600 | 3419 | 692 | 6226 |
| 11 | 9605 | 8644500 | 2136 | 432 | 3890 |
| 12 | 13630 | 12267000 | 3031 | 613 | 5520 |
| 13 | 17892 | 16102800 | 3979 | 805 | 7246 |
| 14 | 11611 | 10449900 | 2582 | 522 | 4702 |
| 15 | 7450 | 6705000 | 1657 | 335 | 3017 |
| 16 | 10931 | 9837900 | 2431 | 492 | 4427 |
| 17 | 16349 | 14714100 | 3636 | 736 | 6621 |
| 18 | 10271 | 9243900 | 2284 | 462 | 4160 |
| 19 | 15941 | 14346900 | 3545 | 717 | 6456 |
| 20 | 15369 | 13832100 | 3418 | 692 | 6224 |
| 21 | 14766 | 13289400 | 3284 | 664 | 5980 |

| SSL ID | Cell count | AREA in Sq.Meters | Area in acres | Area Used in ha | Tons at 9Mg/ha |
|---|---|---|---|---|---|
| 22 | 16868 | 15181200 | 3751 | 759 | 6832 |
| 23 | 13651 | 12285900 | 3036 | 614 | 5529 |
| 24 | 19293 | 17363700 | 4291 | 868 | 7814 |
| 25 | 16116 | 14504400 | 3584 | 725 | 6527 |
| 26 | 16410 | 14769000 | 3649 | 738 | 6646 |
| 27 | 16004 | 14403600 | 3559 | 720 | 6482 |
| 28 | 16552 | 14896800 | 3681 | 745 | 6704 |
| 29 | 17746 | 15971400 | 3947 | 799 | 7187 |
| 30 | 19059 | 17153100 | 4239 | 858 | 7719 |
| 31 | 12662 | 11395800 | 2816 | 570 | 5128 |
| 32 | 15779 | 14201100 | 3509 | 710 | 6390 |
| 33 | 14614 | 13152600 | 3250 | 658 | 5919 |
| 34 | 9234 | 8310600 | 2054 | 416 | 3740 |
| 35 | 9033 | 8129700 | 2009 | 406 | 3658 |
| 36 | 7191 | 6471900 | 1599 | 324 | 2912 |
| 37 | 11196 | 10076400 | 2490 | 504 | 4534 |
| 38 | 12224 | 11001600 | 2719 | 550 | 4951 |
| 39 | 12235 | 11011500 | 2721 | 551 | 4955 |
| 40 | 11183 | 10064700 | 2487 | 503 | 4529 |
| 41 | 12447 | 11202300 | 2768 | 560 | 5041 |
| 42 | 11308 | 10177200 | 2515 | 509 | 4580 |
| 43 | 10143 | 9128700 | 2256 | 456 | 4108 |
| 44 | 9552 | 8596800 | 2124 | 430 | 3869 |
| 45 | 13329 | 11996100 | 2964 | 600 | 5398 |
| 46 | 6172 | 5554800 | 1373 | 278 | 2500 |
| 47 | 6887 | 6198300 | 1532 | 310 | 2789 |
| 48 | 10163 | 9146700 | 2260 | 457 | 4116 |
| 49 | 10959 | 9863100 | 2437 | 493 | 4438 |
| 50 | 13625 | 12262500 | 3030 | 613 | 5518 |
| 51 | 9490 | 8541000 | 2111 | 427 | 3843 |
| 52 | 6244 | 5619600 | 1389 | 281 | 2529 |
| 53 | 9348 | 8413200 | 2079 | 421 | 3786 |
| 54 | 10498 | 9448200 | 2335 | 472 | 4252 |
| 55 | 13894 | 12504600 | 3090 | 625 | 5627 |
| 56 | 8043 | 7238700 | 1789 | 362 | 3257 |
| 57 | 11506 | 10355400 | 2559 | 518 | 4660 |
| 58 | 10121 | 9108900 | 2251 | 455 | 4099 |
| 59 | 9030 | 8127000 | 2008 | 406 | 3657 |
| 60 | 13466 | 12119400 | 2995 | 606 | 5454 |
| 61 | 11730 | 10557000 | 2609 | 528 | 4751 |
| 62 | 7679 | 6911100 | 1708 | 346 | 3110 |
| 63 | 7024 | 6321600 | 1562 | 316 | 2845 |
| 64 | 9629 | 8666100 | 2141 | 433 | 3900 |
| 65 | 12197 | 10977300 | 2713 | 549 | 4940 |

| SSL ID | Cell count | AREA in Sq.Meters | Area in acres | Area Used in ha | Tons at 9Mg/ha |
|---|---|---|---|---|---|
| 66 | 10618 | 9556200 | 2361 | 478 | 4300 |
| 67 | 11319 | 10187100 | 2517 | 509 | 4584 |
| 68 | 12984 | 11685600 | 2888 | 584 | 5259 |
| 69 | 6671 | 6003900 | 1484 | 300 | 2702 |
| 70 | 14178 | 12760200 | 3153 | 638 | 5742 |
| 71 | 9751 | 8775900 | 2169 | 439 | 3949 |
| 72 | 10497 | 9447300 | 2334 | 472 | 4251 |
| 73 | 7351 | 6615900 | 1635 | 331 | 2977 |
| 74 | 10212 | 9190800 | 2271 | 460 | 4136 |
| 75 | 11160 | 10044000 | 2482 | 502 | 4520 |
| 76 | 9561 | 8604900 | 2126 | 430 | 3872 |
| 77 | 10875 | 9787500 | 2419 | 489 | 4404 |
| 78 | 12378 | 11140200 | 2753 | 557 | 5013 |
| 79 | 14685 | 13216500 | 3266 | 661 | 5947 |
| 80 | 10952 | 9856800 | 2436 | 493 | 4436 |
| 81 | 7000 | 6300000 | 1557 | 315 | 2835 |
| 82 | 9155 | 8239500 | 2036 | 412 | 3708 |
| 83 | 7695 | 6925500 | 1711 | 346 | 3116 |
| 84 | 7247 | 6522300 | 1612 | 326 | 2935 |
| 85 | 7741 | 6966900 | 1722 | 348 | 3135 |
| 86 | 7351 | 6615900 | 1635 | 331 | 2977 |
| 87 | 7460 | 6714000 | 1659 | 336 | 3021 |
| 88 | 6889 | 6200100 | 1532 | 310 | 2790 |
| 89 | 7852 | 7066800 | 1746 | 353 | 3180 |
| 90 | 7544 | 6789600 | 1678 | 339 | 3055 |
| 91 | 12553 | 11297700 | 2792 | 565 | 5084 |
| 92 | 7096 | 6386400 | 1578 | 319 | 2874 |
| 93 | 5603 | 5042700 | 1246 | 252 | 2269 |
| 94 | 9969 | 8972100 | 2217 | 449 | 4037 |
| 95 | 9578 | 8620200 | 2130 | 431 | 3879 |
| 96 | 9854 | 8868600 | 2191 | 443 | 3991 |
| 97 | 9209 | 8288100 | 2048 | 414 | 3730 |
| 98 | 15333 | 13799700 | 3410 | 690 | 6210 |
| 99 | 8263 | 7436700 | 1838 | 372 | 3347 |
| 100 | 10179 | 9161100 | 2264 | 458 | 4122 |
| 101 | 13975 | 12577500 | 3108 | 629 | 5660 |
| 102 | 12696 | 11426400 | 2824 | 571 | 5142 |
| 103 | 11276 | 10148400 | 2508 | 507 | 4567 |
| 104 | 14008 | 12607200 | 3115 | 630 | 5673 |
| 105 | 9974 | 8976600 | 2218 | 449 | 4039 |
| 106 | 8694 | 7824600 | 1933 | 391 | 3521 |
| 107 | 15280 | 13752000 | 3398 | 688 | 6188 |
| 108 | 6682 | 6013800 | 1486 | 301 | 2706 |
| 109 | 6135 | 5521500 | 1364 | 276 | 2485 |

| SSL ID | Cell count | AREA in Sq.Meters | Area in acres | Area Used in ha | Tons at 9Mg/ha |
|---|---|---|---|---|---|
| 110 | 10221 | 9198900 | 2273 | 460 | 4139 |
| 111 | 8943 | 8048700 | 1989 | 402 | 3622 |
| 112 | 9205 | 8284500 | 2047 | 414 | 3728 |
| 113 | 12462 | 11215800 | 2771 | 561 | 5047 |
| 114 | 10193 | 9173700 | 2267 | 459 | 4128 |
| 115 | 9457 | 8511300 | 2103 | 426 | 3830 |
| 116 | 9939 | 8945100 | 2210 | 447 | 4025 |
| 117 | 7747 | 6972300 | 1723 | 349 | 3138 |
| 118 | 8693 | 7823700 | 1933 | 391 | 3521 |
| 119 | 8209 | 7388100 | 1826 | 369 | 3325 |
| 120 | 7345 | 6610500 | 1633 | 331 | 2975 |
| 121 | 8135 | 7321500 | 1809 | 366 | 3295 |
| 122 | 12835 | 11551500 | 2854 | 578 | 5198 |
| 123 | 9512 | 8560800 | 2115 | 428 | 3852 |
| 124 | 6610 | 5949000 | 1470 | 297 | 2677 |
| 125 | 6843 | 6158700 | 1522 | 308 | 2771 |
| 126 | 11882 | 10693800 | 2642 | 535 | 4812 |
| 127 | 13451 | 12105900 | 2991 | 605 | 5448 |
| 128 | 9824 | 8841600 | 2185 | 442 | 3979 |
| 129 | 10539 | 9485100 | 2344 | 474 | 4268 |
| 130 | 7071 | 6363900 | 1573 | 318 | 2864 |
| 131 | 10865 | 9778500 | 2416 | 489 | 4400 |
| 132 | 11668 | 10501200 | 2595 | 525 | 4726 |
| 133 | 8792 | 7912800 | 1955 | 396 | 3561 |
| 134 | 10030 | 9027000 | 2231 | 451 | 4062 |
| 135 | 13545 | 12190500 | 3012 | 610 | 5486 |
| 136 | 14542 | 13087800 | 3234 | 654 | 5890 |
| 137 | 15517 | 13965300 | 3451 | 698 | 6284 |
| 138 | 10946 | 9851400 | 2434 | 493 | 4433 |
| 139 | 10141 | 9126900 | 2255 | 456 | 4107 |
| 140 | 8307 | 7476300 | 1847 | 374 | 3364 |
| 141 | 10500 | 9450000 | 2335 | 472 | 4252 |
| 142 | 8702 | 7831800 | 1935 | 392 | 3524 |
| 143 | 10614 | 9552600 | 2360 | 478 | 4299 |
| 144 | 7337 | 6603300 | 1632 | 330 | 2971 |
| 145 | 10610 | 9549000 | 2360 | 477 | 4297 |
| 146 | 10312 | 9280800 | 2293 | 464 | 4176 |
| 147 | 6837 | 6153300 | 1521 | 308 | 2769 |
| 148 | 9501 | 8550900 | 2113 | 428 | 3848 |
| 149 | 9913 | 8921700 | 2205 | 446 | 4015 |
| 150 | 6161 | 5544900 | 1370 | 277 | 2495 |
| 151 | 7305 | 6574500 | 1625 | 329 | 2959 |
| 152 | 7402 | 6661800 | 1646 | 333 | 2998 |
| 153 | 13727 | 12354300 | 3053 | 618 | 5559 |

| SSL ID | Cell count | AREA in Sq.Meters | Area in acres | Area Used in ha | Tons at 9Mg/ha |
|---|---|---|---|---|---|
| 154 | 6993 | 6293700 | 1555 | 315 | 2832 |
| 155 | 7065 | 6358500 | 1571 | 318 | 2861 |

**Table A5. 3 SPV Data, 45% land use rate**

| SSL ID | Cell count | AREA in Sq.Meters | Area in acres | Area Used in ha | Tons at 9Mg/ha |
|---|---|---|---|---|---|
| 1 | 10829 | 9746100 | 2408 | 439 | 3947 |
| 2 | 13030 | 11727000 | 2898 | 528 | 4749 |
| 3 | 12953 | 11657700 | 2881 | 525 | 4721 |
| 4 | 13141 | 11826900 | 2922 | 532 | 4790 |
| 5 | 14045 | 12640500 | 3124 | 569 | 5119 |
| 6 | 8037 | 7233300 | 1787 | 325 | 2929 |
| 7 | 9159 | 8243100 | 2037 | 371 | 3338 |
| 8 | 8733 | 7859700 | 1942 | 354 | 3183 |
| 9 | 8793 | 7913700 | 1956 | 356 | 3205 |
| 10 | 15374 | 13836600 | 3419 | 623 | 5604 |
| 11 | 9605 | 8644500 | 2136 | 389 | 3501 |
| 12 | 13630 | 12267000 | 3031 | 552 | 4968 |
| 13 | 17892 | 16102800 | 3979 | 725 | 6522 |
| 14 | 11611 | 10449900 | 2582 | 470 | 4232 |
| 15 | 7450 | 6705000 | 1657 | 302 | 2716 |
| 16 | 10931 | 9837900 | 2431 | 443 | 3984 |
| 17 | 16349 | 14714100 | 3636 | 662 | 5959 |
| 18 | 10271 | 9243900 | 2284 | 416 | 3744 |
| 19 | 15941 | 14346900 | 3545 | 646 | 5810 |
| 20 | 15369 | 13832100 | 3418 | 622 | 5602 |
| 21 | 14766 | 13289400 | 3284 | 598 | 5382 |
| 22 | 16868 | 15181200 | 3751 | 683 | 6148 |
| 23 | 13651 | 12285900 | 3036 | 553 | 4976 |
| 24 | 19293 | 17363700 | 4291 | 781 | 7032 |
| 25 | 16116 | 14504400 | 3584 | 653 | 5874 |
| 26 | 16410 | 14769000 | 3649 | 665 | 5981 |
| 27 | 16004 | 14403600 | 3559 | 648 | 5833 |
| 28 | 16552 | 14896800 | 3681 | 670 | 6033 |
| 29 | 17746 | 15971400 | 3947 | 719 | 6468 |
| 30 | 19059 | 17153100 | 4239 | 772 | 6947 |
| 31 | 12662 | 11395800 | 2816 | 513 | 4615 |
| 32 | 15779 | 14201100 | 3509 | 639 | 5751 |
| 33 | 14614 | 13152600 | 3250 | 592 | 5327 |

| SSL ID | Cell count | AREA in Sq.Meters | Area in acres | Area Used in ha | Tons at 9Mg/ha |
|---|---|---|---|---|---|
| 34 | 9234 | 8310600 | 2054 | 374 | 3366 |
| 35 | 9033 | 8129700 | 2009 | 366 | 3293 |
| 36 | 7191 | 6471900 | 1599 | 291 | 2621 |
| 37 | 11196 | 10076400 | 2490 | 453 | 4081 |
| 38 | 12224 | 11001600 | 2719 | 495 | 4456 |
| 39 | 12235 | 11011500 | 2721 | 496 | 4460 |
| 40 | 11183 | 10064700 | 2487 | 453 | 4076 |
| 41 | 12447 | 11202300 | 2768 | 504 | 4537 |
| 42 | 11308 | 10177200 | 2515 | 458 | 4122 |
| 43 | 10143 | 9128700 | 2256 | 411 | 3697 |
| 44 | 9552 | 8596800 | 2124 | 387 | 3482 |
| 45 | 13329 | 11996100 | 2964 | 540 | 4858 |
| 46 | 6172 | 5554800 | 1373 | 250 | 2250 |
| 47 | 6887 | 6198300 | 1532 | 279 | 2510 |
| 48 | 10163 | 9146700 | 2260 | 412 | 3704 |
| 49 | 10959 | 9863100 | 2437 | 444 | 3995 |
| 50 | 13625 | 12262500 | 3030 | 552 | 4966 |
| 51 | 9490 | 8541000 | 2111 | 384 | 3459 |
| 52 | 6244 | 5619600 | 1389 | 253 | 2276 |
| 53 | 9348 | 8413200 | 2079 | 379 | 3407 |
| 54 | 10498 | 9448200 | 2335 | 425 | 3827 |
| 55 | 13894 | 12504600 | 3090 | 563 | 5064 |
| 56 | 8043 | 7238700 | 1789 | 326 | 2932 |
| 57 | 11506 | 10355400 | 2559 | 466 | 4194 |
| 58 | 10121 | 9108900 | 2251 | 410 | 3689 |
| 59 | 9030 | 8127000 | 2008 | 366 | 3291 |
| 60 | 13466 | 12119400 | 2995 | 545 | 4908 |
| 61 | 11730 | 10557000 | 2609 | 475 | 4276 |
| 62 | 7679 | 6911100 | 1708 | 311 | 2799 |
| 63 | 7024 | 6321600 | 1562 | 284 | 2560 |
| 64 | 9629 | 8666100 | 2141 | 390 | 3510 |
| 65 | 12197 | 10977300 | 2713 | 494 | 4446 |
| 66 | 10618 | 9556200 | 2361 | 430 | 3870 |
| 67 | 11319 | 10187100 | 2517 | 458 | 4126 |
| 68 | 12984 | 11685600 | 2888 | 526 | 4733 |
| 69 | 6671 | 6003900 | 1484 | 270 | 2432 |
| 70 | 14178 | 12760200 | 3153 | 574 | 5168 |
| 71 | 9751 | 8775900 | 2169 | 395 | 3554 |
| 72 | 10497 | 9447300 | 2334 | 425 | 3826 |
| 73 | 7351 | 6615900 | 1635 | 298 | 2679 |
| 74 | 10212 | 9190800 | 2271 | 414 | 3722 |
| 75 | 11160 | 10044000 | 2482 | 452 | 4068 |
| 76 | 9561 | 8604900 | 2126 | 387 | 3485 |
| 77 | 10875 | 9787500 | 2419 | 440 | 3964 |

| SSL ID | Cell count | AREA in Sq.Meters | Area in acres | Area Used in ha | Tons at 9Mg/ha |
|---|---|---|---|---|---|
| 78 | 12378 | 11140200 | 2753 | 501 | 4512 |
| 79 | 14685 | 13216500 | 3266 | 595 | 5353 |
| 80 | 10952 | 9856800 | 2436 | 444 | 3992 |
| 81 | 7000 | 6300000 | 1557 | 283 | 2551 |
| 82 | 9155 | 8239500 | 2036 | 371 | 3337 |
| 83 | 7695 | 6925500 | 1711 | 312 | 2805 |
| 84 | 7247 | 6522300 | 1612 | 294 | 2642 |
| 85 | 7741 | 6966900 | 1722 | 314 | 2822 |
| 86 | 7351 | 6615900 | 1635 | 298 | 2679 |
| 87 | 7460 | 6714000 | 1659 | 302 | 2719 |
| 88 | 6889 | 6200100 | 1532 | 279 | 2511 |
| 89 | 7852 | 7066800 | 1746 | 318 | 2862 |
| 90 | 7544 | 6789600 | 1678 | 306 | 2750 |
| 91 | 12553 | 11297700 | 2792 | 508 | 4576 |
| 92 | 7096 | 6386400 | 1578 | 287 | 2586 |
| 93 | 5603 | 5042700 | 1246 | 227 | 2042 |
| 94 | 9969 | 8972100 | 2217 | 404 | 3634 |
| 95 | 9578 | 8620200 | 2130 | 388 | 3491 |
| 96 | 9854 | 8868600 | 2191 | 399 | 3592 |
| 97 | 9209 | 8288100 | 2048 | 373 | 3357 |
| 98 | 15333 | 13799700 | 3410 | 621 | 5589 |
| 99 | 8263 | 7436700 | 1838 | 335 | 3012 |
| 100 | 10179 | 9161100 | 2264 | 412 | 3710 |
| 101 | 13975 | 12577500 | 3108 | 566 | 5094 |
| 102 | 12696 | 11426400 | 2824 | 514 | 4628 |
| 103 | 11276 | 10148400 | 2508 | 457 | 4110 |
| 104 | 14008 | 12607200 | 3115 | 567 | 5106 |
| 105 | 9974 | 8976600 | 2218 | 404 | 3636 |
| 106 | 8694 | 7824600 | 1933 | 352 | 3169 |
| 107 | 15280 | 13752000 | 3398 | 619 | 5570 |
| 108 | 6682 | 6013800 | 1486 | 271 | 2436 |
| 109 | 6135 | 5521500 | 1364 | 248 | 2236 |
| 110 | 10221 | 9198900 | 2273 | 414 | 3726 |
| 111 | 8943 | 8048700 | 1989 | 362 | 3260 |
| 112 | 9205 | 8284500 | 2047 | 373 | 3355 |
| 113 | 12462 | 11215800 | 2771 | 505 | 4542 |
| 114 | 10193 | 9173700 | 2267 | 413 | 3715 |
| 115 | 9457 | 8511300 | 2103 | 383 | 3447 |
| 116 | 9939 | 8945100 | 2210 | 403 | 3623 |
| 117 | 7747 | 6972300 | 1723 | 314 | 2824 |
| 118 | 8693 | 7823700 | 1933 | 352 | 3169 |
| 119 | 8209 | 7388100 | 1826 | 332 | 2992 |
| 120 | 7345 | 6610500 | 1633 | 297 | 2677 |
| 121 | 8135 | 7321500 | 1809 | 329 | 2965 |

| SSL ID | Cell count | AREA in Sq.Meters | Area in acres | Area Used in ha | Tons at 9Mg/ha |
|---|---|---|---|---|---|
| 122 | 12835 | 11551500 | 2854 | 520 | 4678 |
| 123 | 9512 | 8560800 | 2115 | 385 | 3467 |
| 124 | 6610 | 5949000 | 1470 | 268 | 2409 |
| 125 | 6843 | 6158700 | 1522 | 277 | 2494 |
| 126 | 11882 | 10693800 | 2642 | 481 | 4331 |
| 127 | 13451 | 12105900 | 2991 | 545 | 4903 |
| 128 | 9824 | 8841600 | 2185 | 398 | 3581 |
| 129 | 10539 | 9485100 | 2344 | 427 | 3841 |
| 130 | 7071 | 6363900 | 1573 | 286 | 2577 |
| 131 | 10865 | 9778500 | 2416 | 440 | 3960 |
| 132 | 11668 | 10501200 | 2595 | 473 | 4253 |
| 133 | 8792 | 7912800 | 1955 | 356 | 3205 |
| 134 | 10030 | 9027000 | 2231 | 406 | 3656 |
| 135 | 13545 | 12190500 | 3012 | 549 | 4937 |
| 136 | 14542 | 13087800 | 3234 | 589 | 5301 |
| 137 | 15517 | 13965300 | 3451 | 628 | 5656 |
| 138 | 10946 | 9851400 | 2434 | 443 | 3990 |
| 139 | 10141 | 9126900 | 2255 | 411 | 3696 |
| 140 | 8307 | 7476300 | 1847 | 336 | 3028 |
| 141 | 10500 | 9450000 | 2335 | 425 | 3827 |
| 142 | 8702 | 7831800 | 1935 | 352 | 3172 |
| 143 | 10614 | 9552600 | 2360 | 430 | 3869 |
| 144 | 7337 | 6603300 | 1632 | 297 | 2674 |
| 145 | 10610 | 9549000 | 2360 | 430 | 3867 |
| 146 | 10312 | 9280800 | 2293 | 418 | 3759 |
| 147 | 6837 | 6153300 | 1521 | 277 | 2492 |
| 148 | 9501 | 8550900 | 2113 | 385 | 3463 |
| 149 | 9913 | 8921700 | 2205 | 401 | 3613 |
| 150 | 6161 | 5544900 | 1370 | 250 | 2246 |
| 151 | 7305 | 6574500 | 1625 | 296 | 2663 |
| 152 | 7402 | 6661800 | 1646 | 300 | 2698 |
| 153 | 13727 | 12354300 | 3053 | 556 | 5003 |
| 154 | 6993 | 6293700 | 1555 | 283 | 2549 |
| 155 | 7065 | 6358500 | 1571 | 286 | 2575 |

**Table A5. 4 SPV Data, 40% land use rate**

| SSL ID | Cell count | AREA in Sq.Meters | Area in acres | Area Used in ha | Tons at 9Mg/ha |
|---|---|---|---|---|---|

| SSL ID | Cell count | AREA in Sq.Meters | Area in acres | Area Used in ha | Tons at 9Mg/ha |
|---|---|---|---|---|---|
| 1 | 10829 | 9746100 | 2408 | 390 | 3509 |
| 2 | 13030 | 11727000 | 2898 | 469 | 4222 |
| 3 | 12953 | 11657700 | 2881 | 466 | 4197 |
| 4 | 13141 | 11826900 | 2922 | 473 | 4258 |
| 5 | 14045 | 12640500 | 3124 | 506 | 4551 |
| 6 | 8037 | 7233300 | 1787 | 289 | 2604 |
| 7 | 9159 | 8243100 | 2037 | 330 | 2968 |
| 8 | 8733 | 7859700 | 1942 | 314 | 2829 |
| 9 | 8793 | 7913700 | 1956 | 317 | 2849 |
| 10 | 15374 | 13836600 | 3419 | 553 | 4981 |
| 11 | 9605 | 8644500 | 2136 | 346 | 3112 |
| 12 | 13630 | 12267000 | 3031 | 491 | 4416 |
| 13 | 17892 | 16102800 | 3979 | 644 | 5797 |
| 14 | 11611 | 10449900 | 2582 | 418 | 3762 |
| 15 | 7450 | 6705000 | 1657 | 268 | 2414 |
| 16 | 10931 | 9837900 | 2431 | 394 | 3542 |
| 17 | 16349 | 14714100 | 3636 | 589 | 5297 |
| 18 | 10271 | 9243900 | 2284 | 370 | 3328 |
| 19 | 15941 | 14346900 | 3545 | 574 | 5165 |
| 20 | 15369 | 13832100 | 3418 | 553 | 4980 |
| 21 | 14766 | 13289400 | 3284 | 532 | 4784 |
| 22 | 16868 | 15181200 | 3751 | 607 | 5465 |
| 23 | 13651 | 12285900 | 3036 | 491 | 4423 |
| 24 | 19293 | 17363700 | 4291 | 695 | 6251 |
| 25 | 16116 | 14504400 | 3584 | 580 | 5222 |
| 26 | 16410 | 14769000 | 3649 | 591 | 5317 |
| 27 | 16004 | 14403600 | 3559 | 576 | 5185 |
| 28 | 16552 | 14896800 | 3681 | 596 | 5363 |
| 29 | 17746 | 15971400 | 3947 | 639 | 5750 |
| 30 | 19059 | 17153100 | 4239 | 686 | 6175 |
| 31 | 12662 | 11395800 | 2816 | 456 | 4102 |
| 32 | 15779 | 14201100 | 3509 | 568 | 5112 |
| 33 | 14614 | 13152600 | 3250 | 526 | 4735 |
| 34 | 9234 | 8310600 | 2054 | 332 | 2992 |
| 35 | 9033 | 8129700 | 2009 | 325 | 2927 |
| 36 | 7191 | 6471900 | 1599 | 259 | 2330 |
| 37 | 11196 | 10076400 | 2490 | 403 | 3627 |
| 38 | 12224 | 11001600 | 2719 | 440 | 3961 |
| 39 | 12235 | 11011500 | 2721 | 440 | 3964 |
| 40 | 11183 | 10064700 | 2487 | 403 | 3623 |
| 41 | 12447 | 11202300 | 2768 | 448 | 4033 |
| 42 | 11308 | 10177200 | 2515 | 407 | 3664 |
| 43 | 10143 | 9128700 | 2256 | 365 | 3286 |
| 44 | 9552 | 8596800 | 2124 | 344 | 3095 |

| SSL ID | Cell count | AREA in Sq.Meters | Area in acres | Area Used in ha | Tons at 9Mg/ha |
|---|---|---|---|---|---|
| 45 | 13329 | 11996100 | 2964 | 480 | 4319 |
| 46 | 6172 | 5554800 | 1373 | 222 | 2000 |
| 47 | 6887 | 6198300 | 1532 | 248 | 2231 |
| 48 | 10163 | 9146700 | 2260 | 366 | 3293 |
| 49 | 10959 | 9863100 | 2437 | 395 | 3551 |
| 50 | 13625 | 12262500 | 3030 | 490 | 4414 |
| 51 | 9490 | 8541000 | 2111 | 342 | 3075 |
| 52 | 6244 | 5619600 | 1389 | 225 | 2023 |
| 53 | 9348 | 8413200 | 2079 | 337 | 3029 |
| 54 | 10498 | 9448200 | 2335 | 378 | 3401 |
| 55 | 13894 | 12504600 | 3090 | 500 | 4502 |
| 56 | 8043 | 7238700 | 1789 | 290 | 2606 |
| 57 | 11506 | 10355400 | 2559 | 414 | 3728 |
| 58 | 10121 | 9108900 | 2251 | 364 | 3279 |
| 59 | 9030 | 8127000 | 2008 | 325 | 2926 |
| 60 | 13466 | 12119400 | 2995 | 485 | 4363 |
| 61 | 11730 | 10557000 | 2609 | 422 | 3801 |
| 62 | 7679 | 6911100 | 1708 | 276 | 2488 |
| 63 | 7024 | 6321600 | 1562 | 253 | 2276 |
| 64 | 9629 | 8666100 | 2141 | 347 | 3120 |
| 65 | 12197 | 10977300 | 2713 | 439 | 3952 |
| 66 | 10618 | 9556200 | 2361 | 382 | 3440 |
| 67 | 11319 | 10187100 | 2517 | 407 | 3667 |
| 68 | 12984 | 11685600 | 2888 | 467 | 4207 |
| 69 | 6671 | 6003900 | 1484 | 240 | 2161 |
| 70 | 14178 | 12760200 | 3153 | 510 | 4594 |
| 71 | 9751 | 8775900 | 2169 | 351 | 3159 |
| 72 | 10497 | 9447300 | 2334 | 378 | 3401 |
| 73 | 7351 | 6615900 | 1635 | 265 | 2382 |
| 74 | 10212 | 9190800 | 2271 | 368 | 3309 |
| 75 | 11160 | 10044000 | 2482 | 402 | 3616 |
| 76 | 9561 | 8604900 | 2126 | 344 | 3098 |
| 77 | 10875 | 9787500 | 2419 | 391 | 3523 |
| 78 | 12378 | 11140200 | 2753 | 446 | 4010 |
| 79 | 14685 | 13216500 | 3266 | 529 | 4758 |
| 80 | 10952 | 9856800 | 2436 | 394 | 3548 |
| 81 | 7000 | 6300000 | 1557 | 252 | 2268 |
| 82 | 9155 | 8239500 | 2036 | 330 | 2966 |
| 83 | 7695 | 6925500 | 1711 | 277 | 2493 |
| 84 | 7247 | 6522300 | 1612 | 261 | 2348 |
| 85 | 7741 | 6966900 | 1722 | 279 | 2508 |
| 86 | 7351 | 6615900 | 1635 | 265 | 2382 |
| 87 | 7460 | 6714000 | 1659 | 269 | 2417 |
| 88 | 6889 | 6200100 | 1532 | 248 | 2232 |

| SSL ID | Cell count | AREA in Sq.Meters | Area in acres | Area Used in ha | Tons at 9Mg/ha |
|---|---|---|---|---|---|
| 89 | 7852 | 7066800 | 1746 | 283 | 2544 |
| 90 | 7544 | 6789600 | 1678 | 272 | 2444 |
| 91 | 12553 | 11297700 | 2792 | 452 | 4067 |
| 92 | 7096 | 6386400 | 1578 | 255 | 2299 |
| 93 | 5603 | 5042700 | 1246 | 202 | 1815 |
| 94 | 9969 | 8972100 | 2217 | 359 | 3230 |
| 95 | 9578 | 8620200 | 2130 | 345 | 3103 |
| 96 | 9854 | 8868600 | 2191 | 355 | 3193 |
| 97 | 9209 | 8288100 | 2048 | 332 | 2984 |
| 98 | 15333 | 13799700 | 3410 | 552 | 4968 |
| 99 | 8263 | 7436700 | 1838 | 297 | 2677 |
| 100 | 10179 | 9161100 | 2264 | 366 | 3298 |
| 101 | 13975 | 12577500 | 3108 | 503 | 4528 |
| 102 | 12696 | 11426400 | 2824 | 457 | 4113 |
| 103 | 11276 | 10148400 | 2508 | 406 | 3653 |
| 104 | 14008 | 12607200 | 3115 | 504 | 4539 |
| 105 | 9974 | 8976600 | 2218 | 359 | 3232 |
| 106 | 8694 | 7824600 | 1933 | 313 | 2817 |
| 107 | 15280 | 13752000 | 3398 | 550 | 4951 |
| 108 | 6682 | 6013800 | 1486 | 241 | 2165 |
| 109 | 6135 | 5521500 | 1364 | 221 | 1988 |
| 110 | 10221 | 9198900 | 2273 | 368 | 3312 |
| 111 | 8943 | 8048700 | 1989 | 322 | 2898 |
| 112 | 9205 | 8284500 | 2047 | 331 | 2982 |
| 113 | 12462 | 11215800 | 2771 | 449 | 4038 |
| 114 | 10193 | 9173700 | 2267 | 367 | 3303 |
| 115 | 9457 | 8511300 | 2103 | 340 | 3064 |
| 116 | 9939 | 8945100 | 2210 | 358 | 3220 |
| 117 | 7747 | 6972300 | 1723 | 279 | 2510 |
| 118 | 8693 | 7823700 | 1933 | 313 | 2817 |
| 119 | 8209 | 7388100 | 1826 | 296 | 2660 |
| 120 | 7345 | 6610500 | 1633 | 264 | 2380 |
| 121 | 8135 | 7321500 | 1809 | 293 | 2636 |
| 122 | 12835 | 11551500 | 2854 | 462 | 4159 |
| 123 | 9512 | 8560800 | 2115 | 342 | 3082 |
| 124 | 6610 | 5949000 | 1470 | 238 | 2142 |
| 125 | 6843 | 6158700 | 1522 | 246 | 2217 |
| 126 | 11882 | 10693800 | 2642 | 428 | 3850 |
| 127 | 13451 | 12105900 | 2991 | 484 | 4358 |
| 128 | 9824 | 8841600 | 2185 | 354 | 3183 |
| 129 | 10539 | 9485100 | 2344 | 379 | 3415 |
| 130 | 7071 | 6363900 | 1573 | 255 | 2291 |
| 131 | 10865 | 9778500 | 2416 | 391 | 3520 |
| 132 | 11668 | 10501200 | 2595 | 420 | 3780 |

| SSL ID | Cell count | AREA in Sq.Meters | Area in acres | Area Used in ha | Tons at 9Mg/ha |
|---|---|---|---|---|---|
| 133 | 8792 | 7912800 | 1955 | 317 | 2849 |
| 134 | 10030 | 9027000 | 2231 | 361 | 3250 |
| 135 | 13545 | 12190500 | 3012 | 488 | 4389 |
| 136 | 14542 | 13087800 | 3234 | 524 | 4712 |
| 137 | 15517 | 13965300 | 3451 | 559 | 5028 |
| 138 | 10946 | 9851400 | 2434 | 394 | 3546 |
| 139 | 10141 | 9126900 | 2255 | 365 | 3286 |
| 140 | 8307 | 7476300 | 1847 | 299 | 2691 |
| 141 | 10500 | 9450000 | 2335 | 378 | 3402 |
| 142 | 8702 | 7831800 | 1935 | 313 | 2819 |
| 143 | 10614 | 9552600 | 2360 | 382 | 3439 |
| 144 | 7337 | 6603300 | 1632 | 264 | 2377 |
| 145 | 10610 | 9549000 | 2360 | 382 | 3438 |
| 146 | 10312 | 9280800 | 2293 | 371 | 3341 |
| 147 | 6837 | 6153300 | 1521 | 246 | 2215 |
| 148 | 9501 | 8550900 | 2113 | 342 | 3078 |
| 149 | 9913 | 8921700 | 2205 | 357 | 3212 |
| 150 | 6161 | 5544900 | 1370 | 222 | 1996 |
| 151 | 7305 | 6574500 | 1625 | 263 | 2367 |
| 152 | 7402 | 6661800 | 1646 | 266 | 2398 |
| 153 | 13727 | 12354300 | 3053 | 494 | 4448 |
| 154 | 6993 | 6293700 | 1555 | 252 | 2266 |
| 155 | 7065 | 6358500 | 1571 | 254 | 2289 |

**Table A5. 5 Travel distance from SSL to the plant**

| SSL no | Tertiary Road Travel (in m) | Secondary Road Travel (in m) | Primary Road Travel (in m) | Total Distance (in m) | Travel Time in Min |
|---|---|---|---|---|---|
| 1 | 0 | 0 | 60157 | 60157 | 41 |
| 2 | 0 | 45013 | 0 | 45013 | 42 |
| 3 | 0 | 7966 | 85714 | 93680 | 66 |
| 4 | 13189 | 23167 | 42068 | 78423 | 67 |
| 5 | 17445 | 0 | 30207 | 47653 | 42 |
| 6 | 10005 | 42137 | 43420 | 95563 | 81 |
| 7 | 40395 | 10976 | 0 | 51370 | 60 |
| 8 | 17703 | 34279 | 0 | 51982 | 54 |
| 9 | 21163 | 25733 | 40604 | 87500 | 78 |
| 10 | 37176 | 4635 | 0 | 41811 | 51 |
| 11 | 13181 | 38898 | 24333 | 76412 | 69 |
| 12 | 13181 | 32638 | 24333 | 70151 | 63 |
| 13 | 13181 | 25862 | 24333 | 63376 | 57 |

| SSL no | Tertiary Road Travel (in m) | Secondary Road Travel (in m) | Primary Road Travel (in m) | Total Distance (in m) | Travel Time in Min |
|---|---|---|---|---|---|
| 14 | 16834 | 32686 | 22450 | 71970 | 67 |
| 15 | 21002 | 23191 | 41103 | 85295 | 76 |
| 16 | 13197 | 23175 | 35164 | 71535 | 62 |
| 17 | 13068 | 23287 | 28405 | 64760 | 57 |
| 18 | 24720 | 20744 | 21984 | 67448 | 65 |
| 19 | 14243 | 21807 | 21984 | 58033 | 53 |
| 20 | 13197 | 37997 | 21984 | 73177 | 67 |
| 21 | 13181 | 31543 | 21984 | 66707 | 61 |
| 22 | 13181 | 24494 | 21984 | 59658 | 54 |
| 23 | 13181 | 18282 | 21984 | 53446 | 48 |
| 24 | 17043 | 13873 | 21984 | 52899 | 49 |
| 25 | 18411 | 11330 | 21984 | 51724 | 48 |
| 26 | 2221 | 0 | 74786 | 77007 | 53 |
| 27 | 0 | 0 | 70344 | 70344 | 48 |
| 28 | 0 | 0 | 63746 | 63746 | 43 |
| 29 | 0 | 2672 | 72179 | 74851 | 51 |
| 30 | 10123 | 0 | 58918 | 69041 | 50 |
| 31 | 2317 | 2655 | 64680 | 69652 | 49 |
| 32 | 4667 | 2704 | 64680 | 72050 | 52 |
| 33 | 13181 | 25235 | 21984 | 60399 | 55 |
| 34 | 26876 | 4635 | 0 | 31511 | 38 |
| 35 | 9382 | 18781 | 21984 | 50147 | 44 |
| 36 | 0 | 18781 | 21984 | 40765 | 32 |
| 37 | 13181 | 8240 | 21984 | 43404 | 37 |
| 38 | 14870 | 5263 | 21984 | 42117 | 38 |
| 39 | 6196 | 1851 | 21984 | 30030 | 24 |
| 40 | 0 | 8819 | 21984 | 30803 | 23 |
| 41 | 1271 | 6695 | 42406 | 50372 | 37 |
| 42 | 6019 | 0 | 36757 | 42776 | 32 |
| 43 | 3299 | 3573 | 47781 | 54653 | 40 |
| 44 | 17043 | 0 | 28147 | 45190 | 40 |
| 45 | 6035 | 0 | 21292 | 27327 | 22 |
| 46 | 0 | 0 | 12199 | 12199 | 8 |
| 47 | 10750 | 0 | 805 | 11555 | 14 |
| 48 | 0 | 0 | 7178 | 7178 | 5 |
| 49 | 18153 | 33989 | 0 | 52143 | 54 |
| 50 | 0 | 36757 | 0 | 36757 | 34 |
| 51 | 0 | 28695 | 0 | 28695 | 27 |
| 52 | 0 | 20873 | 0 | 20873 | 19 |
| 53 | 2124 | 11941 | 0 | 14066 | 14 |

| SSL no | Tertiary Road Travel (in m) | Secondary Road Travel (in m) | Primary Road Travel (in m) | Total Distance (in m) | Travel Time in Min |
|---|---|---|---|---|---|
| 54 | 0 | 7274 | 0 | 7274 | 7 |
| 55 | 0 | 0 | 306 | 306 | 0 |
| 56 | 4458 | 0 | 1947 | 6405 | 7 |
| 57 | 10960 | 0 | 1947 | 12907 | 15 |
| 58 | 7886 | 0 | 8803 | 16689 | 16 |
| 59 | 17123 | 0 | 1947 | 19071 | 23 |
| 60 | 5874 | 16045 | 0 | 21919 | 22 |
| 61 | 0 | 6856 | 0 | 6856 | 6 |
| 62 | 0 | 13438 | 0 | 13438 | 13 |
| 63 | 0 | 25717 | 0 | 25717 | 24 |
| 64 | 5778 | 25733 | 0 | 31511 | 31 |
| 65 | 1255 | 0 | 7628 | 8884 | 7 |
| 66 | 1497 | 0 | 17461 | 18958 | 14 |
| 67 | 3814 | 0 | 14838 | 18652 | 15 |
| 68 | 15546 | 0 | 933 | 16480 | 20 |
| 69 | 7306 | 8932 | 0 | 16238 | 17 |
| 70 | 5858 | 7483 | 10316 | 23657 | 21 |
| 71 | 5858 | 547 | 10316 | 16721 | 15 |
| 72 | 5858 | 14452 | 10316 | 30626 | 28 |
| 73 | 5858 | 22611 | 10316 | 38785 | 35 |
| 74 | 11201 | 8095 | 23448 | 42744 | 37 |
| 75 | 11201 | 1223 | 23448 | 35872 | 31 |
| 76 | 10284 | 202 | 23455 | 33941 | 29 |
| 77 | 19039 | 1883 | 23464 | 44386 | 41 |
| 78 | 19344 | 24494 | 0 | 43839 | 47 |
| 79 | 16480 | 26763 | 10316 | 53559 | 52 |
| 80 | 24011 | 26892 | 10316 | 61219 | 62 |
| 81 | 9366 | 37015 | 10316 | 56697 | 53 |
| 82 | 16399 | 27391 | 10316 | 54106 | 53 |
| 83 | 0 | 0 | 71809 | 71809 | 49 |
| 84 | 3038 | 0 | 25173 | 28212 | 21 |
| 85 | 13583 | 0 | 14838 | 28421 | 27 |
| 86 | 21355 | 3107 | 0 | 24462 | 29 |
| 87 | 26733 | 3104 | 0 | 29837 | 36 |
| 88 | 5311 | 289 | 31190 | 36790 | 28 |
| 89 | 8256 | 5744 | 31189 | 45189 | 37 |
| 90 | 32879 | 4748 | 0 | 37626 | 45 |
| 91 | 32879 | 10784 | 0 | 43663 | 51 |
| 92 | 14388 | 6973 | 31184 | 52545 | 46 |
| 93 | 18218 | 0 | 31173 | 49391 | 44 |

| SSL no | Tertiary Road Travel (in m) | Secondary Road Travel (in m) | Primary Road Travel (in m) | Total Distance (in m) | Travel Time in Min |
|---|---|---|---|---|---|
| 94 | 28276 | 0 | 31189 | 59465 | 56 |
| 95 | 0 | 0 | 70473 | 70473 | 48 |
| 96 | 0 | 2591 | 53044 | 55635 | 38 |
| 97 | 16544 | 0 | 7612 | 24156 | 26 |
| 98 | 7405 | 0 | 7627 | 15031 | 14 |
| 99 | 10525 | 2237 | 15707 | 28469 | 26 |
| 100 | 4200 | 1835 | 15707 | 21742 | 18 |
| 101 | 11861 | 38174 | 0 | 50035 | 50 |
| 102 | 13229 | 38158 | 0 | 51386 | 52 |
| 103 | 21340 | 3573 | 45689 | 70602 | 61 |
| 104 | 11829 | 45931 | 2945 | 60704 | 60 |
| 105 | 19103 | 45931 | 2945 | 67979 | 69 |
| 106 | 5584 | 60817 | 2945 | 69347 | 66 |
| 107 | 13696 | 61541 | 2945 | 78182 | 76 |
| 108 | 0 | 73161 | 2945 | 76106 | 70 |
| 109 | 5729 | 79260 | 2945 | 87935 | 83 |
| 110 | 0 | 86390 | 5713 | 92103 | 84 |
| 111 | 10010 | 36065 | 44160 | 90236 | 76 |
| 112 | 25904 | 32900 | 307 | 59111 | 63 |
| 113 | 45029 | 25733 | 0 | 70763 | 80 |
| 114 | 12997 | 36088 | 38399 | 87484 | 76 |
| 115 | 27439 | 25733 | 0 | 53173 | 58 |
| 116 | 23303 | 25750 | 17510 | 66562 | 65 |
| 117 | 13760 | 36065 | 25138 | 74963 | 68 |
| 118 | 10010 | 25733 | 2414 | 38158 | 38 |
| 119 | 16383 | 25733 | 3396 | 45512 | 47 |
| 120 | 16882 | 25743 | 12521 | 55146 | 53 |
| 121 | 19875 | 25733 | 17526 | 63135 | 61 |
| 122 | 10005 | 32063 | 21292 | 63360 | 57 |
| 123 | 10010 | 31012 | 30223 | 71246 | 62 |
| 124 | 13518 | 25750 | 34858 | 74126 | 64 |
| 125 | 0 | 33667 | 0 | 33667 | 31 |
| 126 | 0 | 40475 | 11153 | 51628 | 45 |
| 127 | 1587 | 45937 | 2945 | 50469 | 47 |
| 128 | 0 | 53688 | 2945 | 56633 | 52 |
| 129 | 6614 | 10992 | 43098 | 60704 | 48 |
| 130 | 10010 | 38850 | 45802 | 94662 | 80 |
| 131 | 1966 | 0 | 76216 | 78182 | 54 |
| 132 | 7462 | 0 | 74566 | 82028 | 60 |
| 133 | 4651 | 0 | 42788 | 47439 | 35 |

| SSL no | Tertiary Road Travel (in m) | Secondary Road Travel (in m) | Primary Road Travel (in m) | Total Distance (in m) | Travel Time in Min |
|---|---|---|---|---|---|
| 134 | 8320 | 50469 | 6952 | 65742 | 62 |
| 135 | 4023 | 53285 | 0 | 57309 | 55 |
| 136 | 0 | 50453 | 11072 | 61525 | 55 |
| 137 | 12939 | 50469 | 1963 | 65372 | 64 |
| 138 | 16174 | 55963 | 90 | 72227 | 72 |
| 139 | 4925 | 50469 | 1963 | 57357 | 54 |
| 140 | 7306 | 55963 | 91 | 63360 | 61 |
| 141 | 0 | 75178 | 91 | 75269 | 70 |
| 142 | 0 | 50453 | 8224 | 58677 | 53 |
| 143 | 9737 | 33989 | 0 | 43726 | 44 |
| 144 | 17671 | 33989 | 0 | 51660 | 54 |
| 145 | 0 | 50437 | 15868 | 66305 | 58 |
| 146 | 0 | 50453 | 24301 | 74754 | 64 |
| 147 | 16866 | 43307 | 27552 | 87725 | 80 |
| 148 | 14001 | 43291 | 25379 | 82672 | 75 |
| 149 | 5858 | 43324 | 31688 | 80870 | 69 |
| 150 | 5858 | 43324 | 25186 | 74368 | 65 |
| 151 | 853 | 16 | 90976 | 91845 | 63 |
| 152 | 0 | 0 | 59803 | 59803 | 41 |
| 153 | 10654 | 39735 | 36741 | 87130 | 75 |
| 154 | 38190 | 3122 | 0 | 41312 | 50 |
| 155 | 11587 | 25733 | 10348 | 47669 | 45 |

# Appendix A6 – Scheduling Trucks and Loaders

## A6.1 - Concorde

Concorde is a symmetric Traveling Salesman Problem solver and uses input data in TSPLIB format. Section A6.1.1 shows a sample of the TSPLIB formatted file used in this study and the corresponding output file from Concorde.

### A6.1.1 File formats:

**Table A6. 1 Sample of the TSPLIB formatted file**

```
NAME : M1L1
COMMENT :
TYPE : TSP
DIMENSION: 16
EDGE_WEIGHT_TYPE : EUC_2D
NODE_COORD_TYPE : TWOD_COORDS
NODE_COORD_SECTION
55      645802.831      4090303.678
48      646219.0125     4097182.637
61      651854.2718     4089577.697
65      641056.0295     4083910.697
54      638801.5945     4090390.709
56      650443.0596     4093482.919
46      646400.8831     4102173.541
62      658273.2714     4089128.87
66      644563.8298     4074081.784
53      632788.8928     4088455.472
47      640977.2423     4097128.111
98      636026.2852     4083546.447
71      638786.7414     4077858.968
67      647017.7321     4079474.573
57      655759.9695     4095519.605
68      652184.5967     4081392.595
EOF
```

Table A6.1 shows a sample TSP problem in TSPLIB format. The TSPLIB format can take different types of datasets, but only one type is described here. The first line contains the name of the dataset. The second line is reserved for comments. The third line describes the problem type and the fourth line has information on the number of nodes in the problem. The fifth line describes the type of line weight and the sixth line describes the data format. The data is stored from line 8. The first word is always a node number. The second word is the x coordinate and the third word is the y coordinate. The number of nodes should match the number of node information entered in line 4. The data file is closed with an EOF statement. This file is then opened using Concorde and solved. The output file can be stored as a .cyc file and opened using any standard text editor

Table A6.2 shows the output file for the TSP dataset from Table A6.1. The first node in the input data file corresponds to the value 0. The second node in the input data file corresponds to the value 1 and so on. The order of the nodes in the output file represents the optimal Hamiltonian cycle output from Concorde.

**Table A6. 2 Output from file Concorde**

| |
|---|
| 0 |
| 2 |
| 5 |
| 14 |
| 7 |
| 15 |
| 13 |
| 8 |
| 12 |
| 3 |
| 11 |
| 9 |
| 4 |
| 10 |
| 6 |
| 1 |

**Table A6. 3 SPV truck and load analysis, 50% land use factor**

| SSL ID | Max No. of Trips per Truck | No. of Trucks | Roundoff calc for days | Loads used for calc |
|---|---|---|---|---|
| 1 | 5 | 3 | 10 | 150 |
| 2 | 5 | 3 | 12 | 180 |
| 3 | 3 | 4 | 12 | 180 |
| 4 | 3 | 4 | 12 | 180 |
| 5 | 5 | 3 | 13 | 195 |
| 6 | 3 | 5 | 7 | 105 |
| 7 | 4 | 4 | 8 | 120 |
| 8 | 4 | 4 | 8 | 120 |
| 9 | 3 | 5 | 8 | 120 |
| 10 | 4 | 4 | 14 | 210 |
| 11 | 3 | 5 | 9 | 135 |
| 12 | 3 | 4 | 12 | 180 |
| 13 | 4 | 4 | 16 | 240 |
| 14 | 3 | 4 | 10 | 150 |
| 15 | 3 | 5 | 6 | 90 |
| 16 | 4 | 4 | 10 | 150 |
| 17 | 4 | 4 | 15 | 225 |
| 18 | 3 | 4 | 9 | 135 |
| 19 | 4 | 4 | 14 | 210 |
| 20 | 3 | 4 | 14 | 210 |
| 21 | 4 | 4 | 13 | 195 |
| 22 | 4 | 4 | 15 | 225 |
| 23 | 4 | 4 | 12 | 180 |
| 24 | 4 | 4 | 18 | 270 |
| 25 | 4 | 4 | 15 | 225 |
| 26 | 4 | 4 | 15 | 225 |
| 27 | 4 | 4 | 15 | 225 |
| 28 | 5 | 3 | 15 | 225 |
| 29 | 4 | 4 | 16 | 240 |
| 30 | 4 | 4 | 17 | 255 |
| 31 | 4 | 4 | 11 | 165 |
| 32 | 4 | 4 | 14 | 210 |
| 33 | 4 | 4 | 13 | 195 |
| 34 | 5 | 3 | 8 | 120 |
| 35 | 5 | 3 | 8 | 120 |
| 36 | 5 | 3 | 6 | 90 |
| 37 | 5 | 3 | 10 | 150 |
| 38 | 5 | 3 | 11 | 165 |
| 39 | 6 | 2 | 11 | 165 |
| 40 | 7 | 2 | 10 | 150 |
| 41 | 5 | 3 | 11 | 165 |
| 42 | 5 | 3 | 10 | 150 |
| 43 | 5 | 3 | 9 | 135 |

| SSL ID | Max No. of Trips per Truck | No. of Trucks | Roundoff calc for days | Loads used for calc |
|---|---|---|---|---|
| 44 | 5 | 3 | 8 | 120 |
| 45 | 7 | 2 | 12 | 180 |
| 46 | 10 | 2 | 5 | 75 |
| 47 | 8 | 2 | 6 | 90 |
| 48 | 11 | 1 | 9 | 135 |
| 49 | 4 | 4 | 10 | 150 |
| 50 | 5 | 3 | 12 | 180 |
| 51 | 6 | 2 | 8 | 120 |
| 52 | 7 | 2 | 5 | 75 |
| 53 | 8 | 2 | 8 | 120 |
| 54 | 10 | 1 | 9 | 135 |
| 55 | 13 | 1 | 13 | 195 |
| 56 | 10 | 1 | 7 | 105 |
| 57 | 8 | 2 | 10 | 150 |
| 58 | 8 | 2 | 9 | 135 |
| 59 | 7 | 2 | 8 | 120 |
| 60 | 7 | 2 | 12 | 180 |
| 61 | 10 | 1 | 10 | 150 |
| 62 | 9 | 2 | 7 | 105 |
| 63 | 6 | 2 | 6 | 90 |
| 64 | 6 | 3 | 9 | 135 |
| 65 | 10 | 1 | 11 | 165 |
| 66 | 8 | 2 | 9 | 135 |
| 67 | 8 | 2 | 10 | 150 |
| 68 | 7 | 2 | 12 | 180 |
| 69 | 8 | 2 | 6 | 90 |
| 70 | 7 | 2 | 13 | 195 |
| 71 | 8 | 2 | 9 | 135 |
| 72 | 6 | 3 | 9 | 135 |
| 73 | 5 | 3 | 6 | 90 |
| 74 | 5 | 3 | 9 | 135 |
| 75 | 6 | 3 | 10 | 150 |
| 76 | 6 | 3 | 8 | 120 |
| 77 | 5 | 3 | 10 | 150 |
| 78 | 4 | 3 | 11 | 165 |
| 79 | 4 | 4 | 13 | 195 |
| 80 | 4 | 4 | 10 | 150 |
| 81 | 4 | 4 | 6 | 90 |
| 82 | 4 | 4 | 8 | 120 |
| 83 | 4 | 4 | 7 | 105 |
| 84 | 7 | 2 | 6 | 90 |
| 85 | 6 | 2 | 7 | 105 |
| 86 | 6 | 3 | 6 | 90 |
| 87 | 5 | 3 | 6 | 90 |

| SSL ID | Max No. of Trips per Truck | No. of Trucks | Roundoff calc for days | Loads used for calc |
|---|---|---|---|---|
| 88 | 6 | 3 | 6 | 90 |
| 89 | 5 | 3 | 7 | 105 |
| 90 | 4 | 3 | 7 | 105 |
| 91 | 4 | 4 | 11 | 165 |
| 92 | 4 | 3 | 6 | 90 |
| 93 | 5 | 3 | 5 | 75 |
| 94 | 4 | 4 | 9 | 135 |
| 95 | 4 | 4 | 8 | 120 |
| 96 | 5 | 3 | 9 | 135 |
| 97 | 6 | 2 | 8 | 120 |
| 98 | 8 | 2 | 14 | 210 |
| 99 | 6 | 2 | 7 | 105 |
| 100 | 7 | 2 | 9 | 135 |
| 101 | 4 | 4 | 13 | 195 |
| 102 | 4 | 4 | 11 | 165 |
| 103 | 4 | 4 | 10 | 150 |
| 104 | 4 | 4 | 13 | 195 |
| 105 | 3 | 5 | 9 | 135 |
| 106 | 3 | 4 | 8 | 120 |
| 107 | 3 | 5 | 14 | 210 |
| 108 | 3 | 5 | 6 | 90 |
| 109 | 3 | 5 | 5 | 75 |
| 110 | 3 | 5 | 9 | 135 |
| 111 | 3 | 5 | 8 | 120 |
| 112 | 4 | 4 | 8 | 120 |
| 113 | 3 | 5 | 11 | 165 |
| 114 | 3 | 5 | 9 | 135 |
| 115 | 4 | 4 | 8 | 120 |
| 116 | 3 | 4 | 9 | 135 |
| 117 | 3 | 5 | 7 | 105 |
| 118 | 5 | 3 | 8 | 120 |
| 119 | 4 | 3 | 7 | 105 |
| 120 | 4 | 4 | 6 | 90 |
| 121 | 4 | 4 | 7 | 105 |
| 122 | 4 | 4 | 12 | 180 |
| 123 | 4 | 4 | 8 | 120 |
| 124 | 3 | 4 | 6 | 90 |
| 125 | 6 | 3 | 6 | 90 |
| 126 | 4 | 3 | 11 | 165 |
| 127 | 4 | 3 | 12 | 180 |
| 128 | 4 | 4 | 9 | 135 |
| 129 | 4 | 4 | 9 | 135 |
| 130 | 3 | 5 | 6 | 90 |
| 131 | 4 | 4 | 10 | 150 |

| SSL ID | Max No. of Trips per Truck | No. of Trucks | Roundoff calc for days | Loads used for calc |
|---|---|---|---|---|
| 132 | 4 | 4 | 10 | 150 |
| 133 | 5 | 3 | 8 | 120 |
| 134 | 4 | 4 | 9 | 135 |
| 135 | 4 | 4 | 12 | 180 |
| 136 | 4 | 4 | 13 | 195 |
| 137 | 3 | 4 | 14 | 210 |
| 138 | 3 | 5 | 10 | 150 |
| 139 | 4 | 4 | 9 | 135 |
| 140 | 4 | 4 | 7 | 105 |
| 141 | 3 | 5 | 9 | 135 |
| 142 | 4 | 4 | 8 | 120 |
| 143 | 5 | 3 | 9 | 135 |
| 144 | 4 | 4 | 6 | 90 |
| 145 | 4 | 4 | 9 | 135 |
| 146 | 3 | 4 | 9 | 135 |
| 147 | 3 | 5 | 6 | 90 |
| 148 | 3 | 5 | 8 | 120 |
| 149 | 3 | 5 | 9 | 135 |
| 150 | 3 | 4 | 5 | 75 |
| 151 | 4 | 4 | 6 | 90 |
| 152 | 5 | 3 | 6 | 90 |
| 153 | 3 | 5 | 12 | 180 |
| 154 | 4 | 4 | 6 | 90 |
| 155 | 4 | 3 | 6 | 90 |

**Table A6. 4 SPV truck and load analysis, 45% land use factor**

| SSL ID | Max No. of Trips per Truck | No. of Trucks | Roundoff calc for days | Loads used for calc |
|---|---|---|---|---|
| 1 | 5 | 3 | 9 | 135 |
| 2 | 5 | 3 | 10 | 150 |
| 3 | 3 | 4 | 10 | 150 |
| 4 | 3 | 4 | 11 | 165 |
| 5 | 5 | 3 | 11 | 165 |
| 6 | 3 | 5 | 6 | 90 |
| 7 | 4 | 4 | 7 | 105 |
| 8 | 4 | 4 | 7 | 105 |
| 9 | 3 | 5 | 7 | 105 |
| 10 | 4 | 4 | 12 | 180 |

| SSL ID | Max No. of Trips per Truck | No. of Trucks | Roundoff calc for days | Loads used for calc |
|---|---|---|---|---|
| 11 | 3 | 5 | 8 | 120 |
| 12 | 3 | 4 | 11 | 165 |
| 13 | 4 | 4 | 15 | 225 |
| 14 | 3 | 4 | 9 | 135 |
| 15 | 3 | 5 | 6 | 90 |
| 16 | 4 | 4 | 9 | 135 |
| 17 | 4 | 4 | 13 | 195 |
| 18 | 3 | 4 | 8 | 120 |
| 19 | 4 | 4 | 13 | 195 |
| 20 | 3 | 4 | 12 | 180 |
| 21 | 4 | 4 | 12 | 180 |
| 22 | 4 | 4 | 14 | 210 |
| 23 | 4 | 4 | 11 | 165 |
| 24 | 4 | 4 | 16 | 240 |
| 25 | 4 | 4 | 13 | 195 |
| 26 | 4 | 4 | 13 | 195 |
| 27 | 4 | 4 | 13 | 195 |
| 28 | 5 | 3 | 13 | 195 |
| 29 | 4 | 4 | 14 | 210 |
| 30 | 4 | 4 | 16 | 240 |
| 31 | 4 | 4 | 10 | 150 |
| 32 | 4 | 4 | 13 | 195 |
| 33 | 4 | 4 | 12 | 180 |
| 34 | 5 | 3 | 7 | 105 |
| 35 | 5 | 3 | 7 | 105 |
| 36 | 5 | 3 | 6 | 90 |
| 37 | 5 | 3 | 9 | 135 |
| 38 | 5 | 3 | 10 | 150 |
| 39 | 6 | 2 | 10 | 150 |
| 40 | 7 | 2 | 9 | 135 |
| 41 | 5 | 3 | 10 | 150 |
| 42 | 5 | 3 | 9 | 135 |
| 43 | 5 | 3 | 8 | 120 |
| 44 | 5 | 3 | 8 | 120 |
| 45 | 7 | 2 | 11 | 165 |
| 46 | 10 | 2 | 5 | 75 |
| 47 | 8 | 2 | 5 | 75 |
| 48 | 11 | 1 | 8 | 120 |
| 49 | 4 | 4 | 9 | 135 |
| 50 | 5 | 3 | 11 | 165 |
| 51 | 6 | 2 | 8 | 120 |
| 52 | 7 | 2 | 5 | 75 |
| 53 | 8 | 2 | 7 | 105 |
| 54 | 10 | 1 | 8 | 120 |

| SSL ID | Max No. of Trips per Truck | No. of Trucks | Roundoff calc for days | Loads used for calc |
|---|---|---|---|---|
| 55 | 13 | 1 | 11 | 165 |
| 56 | 10 | 1 | 6 | 90 |
| 57 | 8 | 2 | 9 | 135 |
| 58 | 8 | 2 | 8 | 120 |
| 59 | 7 | 2 | 7 | 105 |
| 60 | 7 | 2 | 11 | 165 |
| 61 | 10 | 1 | 9 | 135 |
| 62 | 9 | 2 | 6 | 90 |
| 63 | 6 | 2 | 5 | 75 |
| 64 | 6 | 3 | 8 | 120 |
| 65 | 10 | 1 | 10 | 150 |
| 66 | 8 | 2 | 8 | 120 |
| 67 | 8 | 2 | 9 | 135 |
| 68 | 7 | 2 | 10 | 150 |
| 69 | 8 | 2 | 5 | 75 |
| 70 | 7 | 2 | 11 | 165 |
| 71 | 8 | 2 | 8 | 120 |
| 72 | 6 | 3 | 8 | 120 |
| 73 | 5 | 3 | 6 | 90 |
| 74 | 5 | 3 | 8 | 120 |
| 75 | 6 | 3 | 9 | 135 |
| 76 | 6 | 3 | 8 | 120 |
| 77 | 5 | 3 | 9 | 135 |
| 78 | 4 | 3 | 10 | 150 |
| 79 | 4 | 4 | 12 | 180 |
| 80 | 4 | 4 | 9 | 135 |
| 81 | 4 | 4 | 5 | 75 |
| 82 | 4 | 4 | 7 | 105 |
| 83 | 4 | 4 | 6 | 90 |
| 84 | 7 | 2 | 6 | 90 |
| 85 | 6 | 2 | 6 | 90 |
| 86 | 6 | 3 | 6 | 90 |
| 87 | 5 | 3 | 6 | 90 |
| 88 | 6 | 3 | 5 | 75 |
| 89 | 5 | 3 | 6 | 90 |
| 90 | 4 | 3 | 6 | 90 |
| 91 | 4 | 4 | 10 | 150 |
| 92 | 4 | 3 | 5 | 75 |
| 93 | 5 | 3 | 4 | 60 |
| 94 | 4 | 4 | 8 | 120 |
| 95 | 4 | 4 | 8 | 120 |
| 96 | 5 | 3 | 8 | 120 |
| 97 | 6 | 2 | 7 | 105 |
| 98 | 8 | 2 | 12 | 180 |

| SSL ID | Max No. of Trips per Truck | No. of Trucks | Roundoff calc for days | Loads used for calc |
|---|---|---|---|---|
| 99 | 6 | 2 | 6 | 90 |
| 100 | 7 | 2 | 8 | 120 |
| 101 | 4 | 4 | 11 | 165 |
| 102 | 4 | 4 | 10 | 150 |
| 103 | 4 | 4 | 9 | 135 |
| 104 | 4 | 4 | 11 | 165 |
| 105 | 3 | 5 | 8 | 120 |
| 106 | 3 | 4 | 7 | 105 |
| 107 | 3 | 5 | 12 | 180 |
| 108 | 3 | 5 | 5 | 75 |
| 109 | 3 | 5 | 5 | 75 |
| 110 | 3 | 5 | 8 | 120 |
| 111 | 3 | 5 | 7 | 105 |
| 112 | 4 | 4 | 7 | 105 |
| 113 | 3 | 5 | 10 | 150 |
| 114 | 3 | 5 | 8 | 120 |
| 115 | 4 | 4 | 7 | 105 |
| 116 | 3 | 4 | 8 | 120 |
| 117 | 3 | 5 | 6 | 90 |
| 118 | 5 | 3 | 7 | 105 |
| 119 | 4 | 3 | 6 | 90 |
| 120 | 4 | 4 | 6 | 90 |
| 121 | 4 | 4 | 6 | 90 |
| 122 | 4 | 4 | 10 | 150 |
| 123 | 4 | 4 | 8 | 120 |
| 124 | 3 | 4 | 5 | 75 |
| 125 | 6 | 3 | 5 | 75 |
| 126 | 4 | 3 | 10 | 150 |
| 127 | 4 | 3 | 11 | 165 |
| 128 | 4 | 4 | 8 | 120 |
| 129 | 4 | 4 | 8 | 120 |
| 130 | 3 | 5 | 5 | 75 |
| 131 | 4 | 4 | 9 | 135 |
| 132 | 4 | 4 | 9 | 135 |
| 133 | 5 | 3 | 7 | 105 |
| 134 | 4 | 4 | 8 | 120 |
| 135 | 4 | 4 | 11 | 165 |
| 136 | 4 | 4 | 12 | 180 |
| 137 | 3 | 4 | 13 | 195 |
| 138 | 3 | 5 | 9 | 135 |
| 139 | 4 | 4 | 8 | 120 |
| 140 | 4 | 4 | 7 | 105 |
| 141 | 3 | 5 | 8 | 120 |
| 142 | 4 | 4 | 7 | 105 |

| SSL ID | Max No. of Trips per Truck | No. of Trucks | Roundoff calc for days | Loads used for calc |
|---|---|---|---|---|
| 143 | 5 | 3 | 8 | 120 |
| 144 | 4 | 4 | 6 | 90 |
| 145 | 4 | 4 | 8 | 120 |
| 146 | 3 | 4 | 8 | 120 |
| 147 | 3 | 5 | 5 | 75 |
| 148 | 3 | 5 | 8 | 120 |
| 149 | 3 | 5 | 8 | 120 |
| 150 | 3 | 4 | 5 | 75 |
| 151 | 4 | 4 | 6 | 90 |
| 152 | 5 | 3 | 6 | 90 |
| 153 | 3 | 5 | 11 | 165 |
| 154 | 4 | 4 | 5 | 75 |
| 155 | 4 | 3 | 5 | 75 |

**Table A6. 5 SPV truck and load analysis, 40% land use factor**

| SSL ID | Max No. of Trips per Truck | No. of Trucks | Roundoff calc for days | Loads used for calc |
|---|---|---|---|---|
| 1 | 5 | 3 | 8 | 120 |
| 2 | 5 | 3 | 9 | 135 |
| 3 | 3 | 4 | 9 | 135 |
| 4 | 3 | 4 | 9 | 135 |
| 5 | 5 | 3 | 10 | 150 |
| 6 | 3 | 5 | 6 | 90 |
| 7 | 4 | 4 | 6 | 90 |
| 8 | 4 | 4 | 6 | 90 |
| 9 | 3 | 5 | 6 | 90 |
| 10 | 4 | 4 | 11 | 165 |
| 11 | 3 | 5 | 7 | 105 |
| 12 | 3 | 4 | 10 | 150 |
| 13 | 4 | 4 | 13 | 195 |
| 14 | 3 | 4 | 8 | 120 |
| 15 | 3 | 5 | 5 | 75 |
| 16 | 4 | 4 | 8 | 120 |
| 17 | 4 | 4 | 12 | 180 |
| 18 | 3 | 4 | 7 | 105 |
| 19 | 4 | 4 | 11 | 165 |
| 20 | 3 | 4 | 11 | 165 |
| 21 | 4 | 4 | 11 | 165 |
| 22 | 4 | 4 | 12 | 180 |

| SSL ID | Max No. of Trips per Truck | No. of Trucks | Roundoff calc for days | Loads used for calc |
|---|---|---|---|---|
| 23 | 4 | 4 | 10 | 150 |
| 24 | 4 | 4 | 14 | 210 |
| 25 | 4 | 4 | 12 | 180 |
| 26 | 4 | 4 | 12 | 180 |
| 27 | 4 | 4 | 12 | 180 |
| 28 | 5 | 3 | 12 | 180 |
| 29 | 4 | 4 | 13 | 195 |
| 30 | 4 | 4 | 14 | 210 |
| 31 | 4 | 4 | 9 | 135 |
| 32 | 4 | 4 | 11 | 165 |
| 33 | 4 | 4 | 10 | 150 |
| 34 | 5 | 3 | 6 | 90 |
| 35 | 5 | 3 | 6 | 90 |
| 36 | 5 | 3 | 5 | 75 |
| 37 | 5 | 3 | 8 | 120 |
| 38 | 5 | 3 | 9 | 135 |
| 39 | 6 | 2 | 9 | 135 |
| 40 | 7 | 2 | 8 | 120 |
| 41 | 5 | 3 | 9 | 135 |
| 42 | 5 | 3 | 8 | 120 |
| 43 | 5 | 3 | 7 | 105 |
| 44 | 5 | 3 | 7 | 105 |
| 45 | 7 | 2 | 9 | 135 |
| 46 | 10 | 2 | 4 | 60 |
| 47 | 8 | 2 | 5 | 75 |
| 48 | 11 | 1 | 7 | 105 |
| 49 | 4 | 4 | 8 | 120 |
| 50 | 5 | 3 | 10 | 150 |
| 51 | 6 | 2 | 7 | 105 |
| 52 | 7 | 2 | 4 | 60 |
| 53 | 8 | 2 | 7 | 105 |
| 54 | 10 | 1 | 7 | 105 |
| 55 | 13 | 1 | 10 | 150 |
| 56 | 10 | 1 | 6 | 90 |
| 57 | 8 | 2 | 8 | 120 |
| 58 | 8 | 2 | 7 | 105 |
| 59 | 7 | 2 | 6 | 90 |
| 60 | 7 | 2 | 10 | 150 |
| 61 | 10 | 1 | 8 | 120 |
| 62 | 9 | 2 | 5 | 75 |
| 63 | 6 | 2 | 5 | 75 |
| 64 | 6 | 3 | 7 | 105 |
| 65 | 10 | 1 | 9 | 135 |
| 66 | 8 | 2 | 7 | 105 |
| 67 | 8 | 2 | 8 | 120 |

| SSL ID | Max No. of Trips per Truck | No. of Trucks | Roundoff calc for days | Loads used for calc |
|---|---|---|---|---|
| 68 | 7 | 2 | 9 | 135 |
| 69 | 8 | 2 | 5 | 75 |
| 70 | 7 | 2 | 10 | 150 |
| 71 | 8 | 2 | 7 | 105 |
| 72 | 6 | 3 | 7 | 105 |
| 73 | 5 | 3 | 5 | 75 |
| 74 | 5 | 3 | 7 | 105 |
| 75 | 6 | 3 | 8 | 120 |
| 76 | 6 | 3 | 7 | 105 |
| 77 | 5 | 3 | 8 | 120 |
| 78 | 4 | 3 | 9 | 135 |
| 79 | 4 | 4 | 11 | 165 |
| 80 | 4 | 4 | 8 | 120 |
| 81 | 4 | 4 | 5 | 75 |
| 82 | 4 | 4 | 6 | 90 |
| 83 | 4 | 4 | 5 | 75 |
| 84 | 7 | 2 | 5 | 75 |
| 85 | 6 | 2 | 5 | 75 |
| 86 | 6 | 3 | 5 | 75 |
| 87 | 5 | 3 | 5 | 75 |
| 88 | 6 | 3 | 5 | 75 |
| 89 | 5 | 3 | 5 | 75 |
| 90 | 4 | 3 | 5 | 75 |
| 91 | 4 | 4 | 9 | 135 |
| 92 | 4 | 3 | 5 | 75 |
| 93 | 5 | 3 | 4 | 60 |
| 94 | 4 | 4 | 7 | 105 |
| 95 | 4 | 4 | 7 | 105 |
| 96 | 5 | 3 | 7 | 105 |
| 97 | 6 | 2 | 6 | 90 |
| 98 | 8 | 2 | 11 | 165 |
| 99 | 6 | 2 | 6 | 90 |
| 100 | 7 | 2 | 7 | 105 |
| 101 | 4 | 4 | 10 | 150 |
| 102 | 4 | 4 | 9 | 135 |
| 103 | 4 | 4 | 8 | 120 |
| 104 | 4 | 4 | 10 | 150 |
| 105 | 3 | 5 | 7 | 105 |
| 106 | 3 | 4 | 6 | 90 |
| 107 | 3 | 5 | 11 | 165 |
| 108 | 3 | 5 | 5 | 75 |
| 109 | 3 | 5 | 4 | 60 |
| 110 | 3 | 5 | 7 | 105 |
| 111 | 3 | 5 | 6 | 90 |
| 112 | 4 | 4 | 6 | 90 |

| SSL ID | Max No. of Trips per Truck | No. of Trucks | Roundoff calc for days | Loads used for calc |
|---|---|---|---|---|
| 113 | 3 | 5 | 9 | 135 |
| 114 | 3 | 5 | 7 | 105 |
| 115 | 4 | 4 | 7 | 105 |
| 116 | 3 | 4 | 7 | 105 |
| 117 | 3 | 5 | 5 | 75 |
| 118 | 5 | 3 | 6 | 90 |
| 119 | 4 | 3 | 6 | 90 |
| 120 | 4 | 4 | 5 | 75 |
| 121 | 4 | 4 | 6 | 90 |
| 122 | 4 | 4 | 9 | 135 |
| 123 | 4 | 4 | 7 | 105 |
| 124 | 3 | 4 | 4 | 60 |
| 125 | 6 | 3 | 5 | 75 |
| 126 | 4 | 3 | 8 | 120 |
| 127 | 4 | 3 | 10 | 150 |
| 128 | 4 | 4 | 7 | 105 |
| 129 | 4 | 4 | 7 | 105 |
| 130 | 3 | 5 | 5 | 75 |
| 131 | 4 | 4 | 8 | 120 |
| 132 | 4 | 4 | 8 | 120 |
| 133 | 5 | 3 | 6 | 90 |
| 134 | 4 | 4 | 7 | 105 |
| 135 | 4 | 4 | 10 | 150 |
| 136 | 4 | 4 | 10 | 150 |
| 137 | 3 | 4 | 11 | 165 |
| 138 | 3 | 5 | 8 | 120 |
| 139 | 4 | 4 | 7 | 105 |
| 140 | 4 | 4 | 6 | 90 |
| 141 | 3 | 5 | 7 | 105 |
| 142 | 4 | 4 | 6 | 90 |
| 143 | 5 | 3 | 7 | 105 |
| 144 | 4 | 4 | 5 | 75 |
| 145 | 4 | 4 | 7 | 105 |
| 146 | 3 | 4 | 7 | 105 |
| 147 | 3 | 5 | 5 | 75 |
| 148 | 3 | 5 | 7 | 105 |
| 149 | 3 | 5 | 7 | 105 |
| 150 | 3 | 4 | 4 | 60 |
| 151 | 4 | 4 | 5 | 75 |
| 152 | 5 | 3 | 5 | 75 |
| 153 | 3 | 5 | 10 | 150 |
| 154 | 4 | 4 | 5 | 75 |
| 155 | 4 | 3 | 5 | 75 |

## *A6.2 SSL Schedules for Policies 1 – 7, 40%, 45% and 50% Land Use rate*

**Table A6. 6 Policy 1 – 50%**

| Loader 1 | Loader 2 | Loader 3 | Loader 4 | Loader 5 | Loader 6 | Loader 7 | Loader 8 | Loader 9 |
|---|---|---|---|---|---|---|---|---|
| 55 | 67 | 63 | 50 | 145 | 131 | 32 | 24 | 126 |
| 65 | 68 | 86 | 73 | 139 | 82 | 29 | 25 | 5 |
| 66 | 69 | 85 | 74 | 136 | 81 | 10 | 27 | 28 |
| 71 | 60 | 88 | 133 | 135 | 79 | 101 | 129 | 35 |
| 98 | 57 | 76 | 96 | 49 | 142 | 102 | 127 | 143 |
| 53 | 59 | 75 | 89 | 33 | 144 | 83 | 119 | 2 |
| 54 | 58 | 99 | 87 | 17 | 8 | 91 | 155 | 77 |
| 47 | 45 | 72 | 118 | 13 | 22 | 154 | 95 | 152 |
| 46 | 40 | 97 | 43 | 122 | 19 | 30 | 92 | 1 |
| 48 | 52 | 51 | 41 | 94 | 26 | 31 | 78 | 93 |
| 56 | 70 | 36 | 38 | | 128 | | 23 | 90 |
| 62 | 100 | 39 | 37 | | 120 | | | 44 |
| 61 | 84 | 42 | 34 | | | | | |
| | | 125 | | | | | | |
| | | 64 | | | | | | |

**Table A6. 7 Policy 2 - 50%**

| Loader 1 | Loader 2 | Loader 3 | Loader 4 | Loader 5 | Loader 6 | Loader 7 | Loader 8 | Loader 9 |
|---|---|---|---|---|---|---|---|---|
| 55 | 48 | 61 | 65 | 54 | 122 | 145 | 33 | 13 |
| 56 | 46 | 62 | 66 | 53 | 136 | 135 | 49 | 94 |
| 47 | 98 | 71 | 67 | 57 | 22 | 131 | 144 | 139 |
| 58 | 69 | 100 | 52 | 68 | 120 | 26 | 19 | 8 |
| 84 | 70 | 45 | 60 | 59 | 142 | 82 | 32 | 81 |
| 40 | 63 | 39 | 97 | 99 | 102 | 128 | 91 | 79 |
| 51 | 85 | 72 | 88 | 76 | 154 | 10 | 30 | 29 |
| 86 | 75 | 64 | 125 | 42 | 24 | 31 | 25 | 101 |
| 36 | 50 | 133 | 73 | 87 | 95 | 23 | 129 | 83 |
| 41 | 89 | 37 | 74 | 34 | 127 | 78 | 92 | 27 |
| 118 | 38 | 96 | 43 | 44 | 143 | 126 | | 119 |
| 152 | 1 | 77 | 2 | 5 | | | | |
| 28 | 93 | | 35 | 90 | | | | |
| 155 | | | 119 | | | | | |

**Table A6. 8 Policy 3 - 50%**

| Loader 1 | Loader 2 | Loader 3 | Loader 4 | Loader 5 | Loader 6 | Loader 7 | Loader 8 | Loader 9 |
|---|---|---|---|---|---|---|---|---|
| 55 | 67 | 63 | 50 | 94 | 131 | 32 | 24 | 126 |
| 65 | 68 | 86 | 73 | 33 | 82 | 29 | 25 | 5 |
| 66 | 69 | 85 | 74 | 135 | 81 | 10 | 27 | 28 |

| Loader 1 | Loader 2 | Loader 3 | Loader 4 | Loader 5 | Loader 6 | Loader 7 | Loader 8 | Loader 9 |
|---|---|---|---|---|---|---|---|---|
| 71 | 60 | 88 | 133 | 136 | 79 | 101 | 129 | 35 |
| 98 | 57 | 76 | 96 | 139 | 142 | 102 | 127 | 143 |
| 53 | 59 | 75 | 89 | 49 | 144 | 83 | 119 | 2 |
| 54 | 58 | 99 | 87 | | 8 | 91 | 155 | 77 |
| 47 | 45 | 72 | 118 | | 22 | 154 | 95 | 152 |
| 46 | 40 | 97 | 43 | | 19 | 30 | 92 | 1 |
| 48 | 52 | 51 | 41 | | 26 | 31 | 78 | 93 |
| 56 | 70 | 36 | 38 | | 128 | | 23 | 90 |
| 62 | 100 | 39 | 37 | | 120 | | | 44 |
| 61 | 84 | 42 | 34 | | | | | |
| | | 125 | | | | | | |
| | | 64 | | | | | | |

**Table A6. 9 Policy 4 - 50%**

| Loader 1 | Loader 2 | Loader 3 | Loader 4 | Loader 5 | Loader 6 | Loader 7 | Loader 8 | Loader 9 |
|---|---|---|---|---|---|---|---|---|
| 55 | 67 | 63 | 50 | 145 | 131 | 32 | 24 | 126 |
| 48 | 57 | 39 | 133 | 17 | 22 | 102 | 25 | 90 |
| 61 | 58 | 97 | 73 | 13 | 8 | 29 | 23 | 35 |
| 65 | 69 | 99 | 87 | 122 | 144 | 91 | 95 | 143 |
| 54 | 100 | 51 | 41 | 94 | 26 | 10 | 27 | 93 |
| 56 | 52 | 85 | 89 | 33 | 120 | 154 | 129 | 28 |
| 46 | 68 | 72 | 37 | 135 | 81 | 101 | 78 | 5 |
| 62 | 84 | 88 | 74 | 136 | 19 | 30 | 127 | 2 |
| 66 | 70 | 76 | 34 | 139 | 82 | 31 | 119 | 77 |
| 53 | 45 | 86 | 118 | 49 | 142 | 83 | 92 | 1 |
| 47 | 60 | 75 | 38 | | 79 | | 155 | 152 |
| 98 | 59 | 64 | 96 | | 128 | | | 44 |
| 71 | 40 | 125 | 43 | | | | | |
| | | 42 | | | | | | |
| | | 36 | | | | | | |

**Table A6. 10 Policy 5 - 50%**

| Loader 1 | Loader 2 | Loader 3 | Loader 4 | Loader 5 | Loader 6 | Loader 7 | Loader 8 | Loader 9 |
|---|---|---|---|---|---|---|---|---|
| 54 | 136 | 55 | 32 | 56 | 122 | 65 | 96 | 81 |
| 47 | 22 | 48 | 31 | 61 | 91 | 67 | 1 | 82 |
| 34 | 19 | 46 | 30 | 62 | 154 | 68 | 95 | 73 |
| 35 | 24 | 40 | 28 | 69 | 155 | 86 | 131 | 72 |
| 10 | 23 | 36 | 27 | 87 | 119 | 85 | 94 | 98 |
| 144 | 33 | 37 | 26 | 118 | 126 | 84 | 93 | 53 |
| 143 | 8 | 25 | 13 | 63 | 5 | 66 | 92 | 97 |
| 2 | 49 | 38 | 29 | 64 | 43 | 100 | 90 | 78 |
| 142 | 135 | 39 | | 125 | 129 | 75 | 89 | 79 |
| 101 | 139 | 41 | | 44 | 127 | 74 | 88 | 102 |
| 50 | | 42 | | 45 | 128 | 99 | 76 | 145 |

| Loader 1 | Loader 2 | Loader 3 | Loader 4 | Loader 5 | Loader 6 | Loader 7 | Loader 8 | Loader 9 |
|---|---|---|---|---|---|---|---|---|
| 51 | | 58 | | 49 | 120 | 70 | 77 | 146 |
| 52 | | | | 50 | | 71 | 83 | 80 |
| | | | | 60 | | | 152 | |
| | | | | 57 | | | 133 | |

**Table A6. 11 Policy 6 - 50%**

| Loader 1 | Loader 2 | Loader 3 | Loader 4 | Loader 5 | Loader 6 | Loader 7 | Loader 8 | Loader 9 |
|---|---|---|---|---|---|---|---|---|
| 55 | 67 | 63 | 50 | 94 | 131 | 32 | 24 | 126 |
| 48 | 68 | 86 | 73 | 33 | 82 | 29 | 25 | 5 |
| 61 | 69 | 85 | 74 | 49 | 81 | 10 | 27 | 28 |
| 65 | 60 | 88 | 133 | 135 | 79 | 101 | 129 | 35 |
| 54 | 57 | 76 | 96 | 136 | 142 | 102 | 127 | 143 |
| 56 | 59 | 75 | 89 | 139 | 144 | 83 | 119 | 2 |
| 46 | 58 | 99 | 87 | | 8 | 91 | 155 | 77 |
| 62 | 45 | 72 | 118 | | 22 | 154 | 95 | 152 |
| 66 | 40 | 97 | 43 | | 19 | 30 | 92 | 1 |
| 53 | 52 | 51 | 41 | | 26 | 31 | 78 | 93 |
| 47 | 70 | 36 | 38 | | 128 | | 23 | 90 |
| 98 | 100 | 39 | 37 | | 120 | | | 44 |
| 71 | 84 | 42 | 34 | | | | | |
| | | 125 | | | | | | |
| | | 64 | | | | | | |

**Table A6. 12 Policy 7 - 50%**

| Loader 1 | Loader 2 | Loader 3 | Loader 4 | Loader 5 | Loader 6 | Loader 7 | Loader 8 | Loader 9 |
|---|---|---|---|---|---|---|---|---|
| 54 | 136 | 55 | 32 | 56 | 122 | 65 | 96 | 73 |
| 47 | 22 | 48 | 31 | 61 | 91 | 67 | 1 | 72 |
| 34 | 19 | 46 | 30 | 62 | 154 | 68 | 95 | 98 |
| 35 | 24 | 40 | 28 | 69 | 155 | 86 | 131 | 53 |
| 10 | 23 | 36 | 27 | 87 | 119 | 85 | 94 | 97 |
| 144 | 33 | 37 | 26 | 118 | 126 | 84 | 93 | 78 |
| 143 | 8 | 25 | 13 | 63 | 5 | 66 | 92 | 82 |
| 2 | 49 | 38 | 29 | 64 | 43 | 100 | 90 | |
| 142 | 135 | 39 | | 125 | 129 | 75 | 89 | |
| 101 | 139 | 41 | | 44 | 127 | 74 | 88 | |
| 50 | | 42 | | 45 | 128 | 99 | 76 | |
| 51 | | 58 | | 49 | 120 | 70 | 77 | |
| 52 | | | | 50 | | 71 | 83 | |
| | | | | 60 | | | 152 | |
| | | | | 57 | | | 133 | |

**Table A6. 13 Policy 1 - 45%**

| Loader 1 | Loader 2 | Loader 3 | Loader 4 | Loader 5 | Loader 6 | Loader 7 | Loader 8 | Loader 9 |
|---|---|---|---|---|---|---|---|---|
| 55 | 58 | 99 | 41 | 80 | 13 | 144 | 91 | 27 |
| 48 | 69 | 51 | 89 | 123 | 122 | 26 | 10 | 129 |
| 61 | 100 | 85 | 37 | 16 | 94 | 120 | 154 | 78 |
| 65 | 52 | 72 | 74 | 140 | 33 | 81 | 101 | 127 |
| 54 | 68 | 88 | 34 | 103 | 135 | 19 | 30 | 119 |
| 56 | 84 | 76 | 118 | 21 | 136 | 82 | 31 | 92 |
| 46 | 70 | 86 | 38 | 121 | 139 | 142 | 24 | 155 |
| 62 | 45 | 75 | 96 | 7 | 49 | 79 | 83 | 126 |
| 66 | 60 | 64 | 43 | 132 | 131 | 32 | 25 | 90 |
| 53 | 59 | 125 | 44 | 104 | 22 | 128 | 23 | 35 |
| 47 | 40 | 42 | 152 | 115 | 8 | 102 | 95 | 143 |
| 98 | 63 | 36 | 1 | 145 |  | 29 |  | 93 |
| 71 | 39 | 50 | 77 | 17 |  |  |  | 28 |
| 67 | 97 | 133 | 2 |  |  |  |  | 5 |
| 57 |  | 73 |  |  |  |  |  |  |
|  |  | 87 |  |  |  |  |  |  |

**Table A6. 14 Policy 2 - 45%**

| Loader 1 | Loader 2 | Loader 3 | Loader 4 | Loader 5 | Loader 6 | Loader 7 | Loader 8 | Loader 9 |
|---|---|---|---|---|---|---|---|---|
| 55 | 48 | 61 | 65 | 54 | 123 | 121 | 21 | 132 |
| 56 | 46 | 62 | 66 | 53 | 16 | 115 | 104 | 17 |
| 47 | 98 | 71 | 67 | 57 | 140 | 122 | 13 | 33 |
| 58 | 69 | 100 | 52 | 68 | 103 | 136 | 135 | 49 |
| 84 | 70 | 45 | 60 | 59 | 7 | 22 | 131 | 144 |
| 40 | 63 | 39 | 97 | 99 | 145 | 120 | 26 | 19 |
| 51 | 85 | 72 | 88 | 76 | 94 | 142 | 82 | 32 |
| 86 | 75 | 64 | 125 | 42 | 139 | 102 | 128 | 91 |
| 36 | 50 | 133 | 73 | 87 | 8 | 154 | 10 | 30 |
| 41 | 89 | 37 | 74 | 34 | 91 | 24 | 31 | 25 |
| 118 | 38 | 96 | 43 | 44 | 79 | 27 | 23 |  |
| 152 | 1 | 77 | 2 | 5 | 29 | 78 |  |  |
| 28 | 93 | 143 | 35 | 90 | 101 |  |  |  |
| 126 | 155 | 92 | 119 | 127 |  |  |  |  |
| 83 | 129 |  | 95 |  |  |  |  |  |

**Table A6. 15 Policy 3 - 45%**

| Loader 1 | Loader 2 | Loader 3 | Loader 4 | Loader 5 | Loader 6 | Loader 7 | Loader 8 | Loader 9 |
|---|---|---|---|---|---|---|---|---|
| 55 | 58 | 99 | 41 | 121 | 13 | 144 | 91 | 27 |
| 48 | 69 | 51 | 89 | 7 | 122 | 26 | 10 | 129 |
| 61 | 100 | 85 | 37 | 132 | 94 | 120 | 154 | 78 |
| 65 | 52 | 72 | 74 | 104 | 33 | 81 | 101 | 127 |
| 54 | 68 | 88 | 34 | 115 | 135 | 19 | 30 | 119 |
| 56 | 84 | 76 | 118 | 145 | 136 | 82 | 31 | 92 |

| Loader 1 | Loader 2 | Loader 3 | Loader 4 | Loader 5 | Loader 6 | Loader 7 | Loader 8 | Loader 9 |
|---|---|---|---|---|---|---|---|---|
| 46 | 70 | 86 | 38 | 17 | 139 | 142 | 24 | 155 |
| 62 | 45 | 75 | 96 | | 49 | 79 | 83 | 126 |
| 66 | 60 | 64 | 43 | | 131 | 32 | 25 | 90 |
| 53 | 59 | 125 | 44 | | 22 | 128 | 23 | 35 |
| 47 | 40 | 42 | 152 | | 8 | 102 | 95 | 143 |
| 98 | 63 | 36 | 1 | | | 29 | | 93 |
| 71 | 39 | 50 | 77 | | | | | 28 |
| 67 | 97 | 133 | 2 | | | | | 5 |
| 57 | | 73 | | | | | | |
| | | 87 | | | | | | |

**Table A6. 16 Policy 4 - 45%**

| Loader 1 | Loader 2 | Loader 3 | Loader 4 | Loader 5 | Loader 6 | Loader 7 | Loader 8 | Loader 9 |
|---|---|---|---|---|---|---|---|---|
| 55 | 58 | 99 | 41 | 80 | 13 | 144 | 91 | 27 |
| 61 | 59 | 72 | 38 | 132 | 22 | 142 | 95 | 35 |
| 62 | 60 | 73 | 37 | 7 | 33 | 102 | 83 | 143 |
| 57 | 63 | 50 | 34 | 123 | 8 | 79 | 101 | 78 |
| 56 | 69 | 51 | 2 | 121 | 49 | 81 | 10 | 93 |
| 48 | 68 | 36 | 74 | 115 | 135 | 82 | 23 | 92 |
| 46 | 84 | 42 | 77 | 104 | 136 | 120 | 24 | 90 |
| 47 | 100 | 125 | 152 | 103 | 139 | 128 | 25 | 155 |
| 54 | 70 | 64 | 96 | 17 | 94 | 32 | 30 | 119 |
| 53 | 97 | 87 | 1 | 16 | 131 | 29 | 31 | 127 |
| 98 | 52 | 86 | 89 | 21 | 122 | 26 | 154 | 126 |
| 71 | 40 | 85 | 118 | 140 | | 19 | | 5 |
| 66 | 39 | 88 | 44 | 145 | | | | 129 |
| 67 | 45 | 133 | 43 | | | | | 28 |
| 65 | | 76 | | | | | | |
| | | 75 | | | | | | |

**Table A6. 17 Policy 5 - 45%**

| Loader 1 | Loader 2 | Loader 3 | Loader 4 | Loader 5 | Loader 6 | Loader 7 | Loader 8 | Loader 9 |
|---|---|---|---|---|---|---|---|---|
| 54 | 136 | 55 | 32 | 56 | 123 | 65 | 7 | 81 |
| 52 | 139 | 48 | 31 | 61 | 122 | 70 | 91 | 82 |
| 51 | 140 | 46 | 41 | 62 | 121 | 99 | 90 | 83 |
| 50 | 2 | 40 | 28 | 69 | 120 | 74 | 92 | 73 |
| 101 | 8 | 36 | 30 | 87 | 115 | 75 | 89 | 72 |
| 142 | 22 | 37 | 27 | 118 | 128 | 76 | 88 | 98 |
| 143 | 19 | 24 | 26 | 63 | 127 | 84 | 77 | 53 |
| 144 | 16 | 25 | 17 | 64 | 104 | 85 | 152 | 97 |
| 10 | 21 | 38 | 13 | 125 | 103 | 86 | 133 | 78 |
| 33 | 49 | 39 | 29 | 44 | 129 | 68 | 96 | 79 |
| 23 | 135 | 42 | | 5 | 43 | 67 | 1 | 102 |
| 35 | | 58 | | 45 | 126 | 66 | 93 | 145 |

| Loader 1 | Loader 2 | Loader 3 | Loader 4 | Loader 5 | Loader 6 | Loader 7 | Loader 8 | Loader 9 |
|---|---|---|---|---|---|---|---|---|
| 34 | | | | 59 | 119 | 100 | 94 | 146 |
| 47 | | | | 60 | 155 | 71 | 95 | 80 |
| | | | | 57 | 154 | | 131 | |
| | | | | | | | 132 | |

**Table A6. 18 Policy 6 - 45%**

| Loader 1 | Loader 2 | Loader 3 | Loader 4 | Loader 5 | Loader 6 | Loader 7 | Loader 8 | Loader 9 |
|---|---|---|---|---|---|---|---|---|
| 55 | 58 | 99 | 41 | 121 | 13 | 144 | 91 | 27 |
| 61 | 59 | 72 | 38 | 7 | 22 | 142 | 95 | 35 |
| 62 | 60 | 73 | 37 | 132 | 33 | 102 | 83 | 143 |
| 57 | 63 | 50 | 34 | 145 | 8 | 79 | 101 | 78 |
| 56 | 69 | 51 | 2 | 17 | 49 | 81 | 10 | 93 |
| 48 | 68 | 36 | 74 | 104 | 135 | 82 | 23 | 92 |
| 46 | 84 | 42 | 77 | 115 | 136 | 120 | 24 | 90 |
| 47 | 100 | 125 | 152 | | 139 | 128 | 25 | 155 |
| 54 | 70 | 64 | 96 | | 94 | 32 | 30 | 119 |
| 53 | 97 | 87 | 1 | | 131 | 29 | 31 | 127 |
| 98 | 52 | 86 | 89 | | 122 | 26 | 154 | 126 |
| 71 | 40 | 85 | 118 | | | 19 | | 5 |
| 66 | 39 | 88 | 44 | | | | | 129 |
| 67 | 45 | 133 | 43 | | | | | 28 |
| 65 | | 76 | | | | | | |
| | | 75 | | | | | | |

**Table A6. 19 Policy 7 - 45%**

| Loader 1 | Loader 2 | Loader 3 | Loader 4 | Loader 5 | Loader 6 | Loader 7 | Loader 8 | Loader 9 |
|---|---|---|---|---|---|---|---|---|
| 54 | 136 | 55 | 32 | 56 | 123 | 65 | 7 | 82 |
| 52 | 139 | 48 | 31 | 61 | 122 | 70 | 91 | 83 |
| 51 | 140 | 46 | 41 | 62 | 121 | 99 | 90 | 73 |
| 50 | 2 | 40 | 28 | 69 | 120 | 74 | 92 | 72 |
| 101 | 8 | 36 | 30 | 87 | 115 | 75 | 89 | 98 |
| 142 | 22 | 37 | 27 | 118 | 128 | 76 | 88 | 53 |
| 143 | 19 | 24 | 26 | 63 | 127 | 84 | 77 | 97 |
| 144 | 16 | 25 | 17 | 64 | 104 | 85 | 152 | 78 |
| 10 | 21 | 38 | 13 | 125 | 103 | 86 | 133 | |
| 33 | 49 | 39 | 29 | 44 | 129 | 68 | 96 | |
| 23 | 135 | 42 | | 5 | 43 | 67 | 1 | |
| 35 | | 58 | | 45 | 126 | 66 | 93 | |
| 34 | | | | 59 | 119 | 100 | 94 | |
| 47 | | | | 60 | 155 | 71 | 95 | |
| | | | | 57 | 154 | | 131 | |
| | | | | | | | 132 | |

**Table A6. 20 Policy 1 - 40%**

| Loader 1 | Loader 2 | Loader 3 | Loader 4 | Loader 5 | Loader 6 | Loader 7 | Loader 8 | Loader 9 |
|---|---|---|---|---|---|---|---|---|
| 55 | 69 | 72 | 34 | 14 | 16 | 33 | 142 | 24 |
| 48 | 100 | 88 | 118 | 4 | 140 | 135 | 79 | 83 |
| 61 | 52 | 76 | 38 | 106 | 103 | 136 | 32 | 25 |
| 65 | 68 | 86 | 96 | 3 | 21 | 139 | 128 | 23 |
| 54 | 84 | 75 | 43 | 18 | 121 | 49 | 102 | 95 |
| 56 | 70 | 64 | 44 | 116 | 7 | 131 | 29 | 27 |
| 46 | 45 | 125 | 152 | 150 | 132 | 22 | 91 | 129 |
| 62 | 60 | 42 | 1 | 137 | 104 | 8 | 10 | 78 |
| 66 | 59 | 36 | 77 | 124 | 115 | 144 | 154 | 127 |
| 53 | 40 | 50 | 2 | 146 | 145 | 26 | 101 | 119 |
| 47 | 63 | 133 | 5 | 12 | 17 | 120 | 30 | 92 |
| 98 | 39 | 73 | 28 | 112 | 13 | 81 | 31 | 155 |
| 71 | 97 | 87 | 93 | 151 | 122 | 19 | | 126 |
| 67 | 99 | 41 | 143 | 134 | 94 | 82 | | 80 |
| 57 | 51 | 89 | 35 | 80 | | | | |
| 68 | 85 | 37 | | 123 | | | | |
| | | 74 | | | | | | |

**Table A6. 21 Policy 2 - 40%**

| Loader 1 | Loader 2 | Loader 3 | Loader 4 | Loader 5 | Loader 6 | Loader 7 | Loader 8 | Loader 9 |
|---|---|---|---|---|---|---|---|---|
| 55 | 48 | 61 | 65 | 54 | 11 | 3 | 117 | 105 |
| 56 | 46 | 62 | 66 | 53 | 14 | 137 | 106 | 20 |
| 47 | 98 | 71 | 67 | 57 | 18 | 112 | 150 | 4 |
| 58 | 69 | 100 | 52 | 68 | 124 | 123 | 12 | 116 |
| 84 | 70 | 45 | 60 | 59 | 151 | 21 | 80 | 146 |
| 40 | 63 | 39 | 97 | 99 | 16 | 104 | 103 | 134 |
| 51 | 85 | 72 | 88 | 76 | 121 | 13 | 132 | 140 |
| 86 | 75 | 64 | 125 | 42 | 115 | 135 | 17 | 7 |
| 36 | 50 | 133 | 73 | 87 | 122 | 131 | 33 | 145 |
| 41 | 89 | 37 | 74 | 34 | 136 | 26 | 49 | 94 |
| 118 | 38 | 96 | 43 | 44 | 22 | 82 | 114 | 139 |
| 152 | 1 | 77 | 2 | 5 | 120 | 128 | 19 | 8 |
| 28 | 93 | 143 | 35 | 90 | 142 | 101 | 32 | 81 |
| 126 | 155 | 92 | 119 | 127 | 102 | | 10 | 79 |
| 78 | 129 | 27 | 95 | 23 | 24 | | | 29 |
| 25 | 83 | | 31 | 30 | | | | |
| | 154 | | 91 | | | | | |

**Table A6. 22 Policy 3 - 40%**

| Loader 1 | Loader 2 | Loader 3 | Loader 4 | Loader 5 | Loader 6 | Loader 7 | Loader 8 | Loader 9 |
|---|---|---|---|---|---|---|---|---|
| 55 | 69 | 72 | 34 | 137 | 16 | 33 | 142 | 24 |
| 48 | 100 | 88 | 118 | 124 | 140 | 135 | 79 | 83 |

| Loader 1 | Loader 2 | Loader 3 | Loader 4 | Loader 5 | Loader 6 | Loader 7 | Loader 8 | Loader 9 |
|---|---|---|---|---|---|---|---|---|
| 61 | 52 | 76 | 38 | 146 | 103 | 136 | 32 | 25 |
| 65 | 68 | 86 | 96 | 12 | 21 | 139 | 128 | 23 |
| 54 | 84 | 75 | 43 | 112 | 121 | 49 | 102 | 95 |
| 56 | 70 | 64 | 44 | 151 | 7 | 131 | 29 | 27 |
| 46 | 45 | 125 | 152 | 134 | 132 | 22 | 91 | 129 |
| 62 | 60 | 42 | 1 | 80 | 104 | 8 | 10 | 78 |
| 66 | 59 | 36 | 77 | 123 | 115 | 144 | 154 | 127 |
| 53 | 40 | 50 | 2 | | 145 | 26 | 101 | 119 |
| 47 | 63 | 133 | 5 | | 17 | 120 | 30 | 92 |
| 98 | 39 | 73 | 28 | | 13 | 81 | 31 | 155 |
| 71 | 97 | 87 | 93 | | 122 | 19 | | 126 |
| 67 | 99 | 41 | 143 | | 94 | 82 | | 80 |
| 57 | 51 | 89 | 35 | | | | | |
| 68 | 85 | 37 | | | | | | |
| | | 74 | | | | | | |

**Table A6. 23 Policy 4 - 40%**

| Loader 1 | Loader 2 | Loader 3 | Loader 4 | Loader 5 | Loader 6 | Loader 7 | Loader 8 | Loader 9 |
|---|---|---|---|---|---|---|---|---|
| 55 | 69 | 72 | 34 | 14 | 16 | 33 | 142 | 24 |
| 61 | 68 | 50 | 35 | 12 | 21 | 144 | 101 | 23 |
| 56 | 85 | 36 | 38 | 3 | 140 | 8 | 10 | 78 |
| 57 | 84 | 37 | 28 | 106 | 145 | 49 | 29 | 80 |
| 62 | 100 | 41 | 43 | 112 | 94 | 135 | 32 | 83 |
| 68 | 99 | 42 | 5 | 116 | 132 | 136 | 31 | 92 |
| 67 | 70 | 125 | 44 | 123 | 7 | 139 | 30 | 95 |
| 66 | 97 | 64 | 118 | 124 | 122 | 81 | 128 | 155 |
| 71 | 52 | 87 | 93 | 151 | 121 | 82 | 154 | 119 |
| 65 | 51 | 86 | 1 | 150 | 115 | 131 | 91 | 127 |
| 98 | 40 | 89 | 96 | 80 | 104 | 120 | 79 | 126 |
| 53 | 39 | 88 | 152 | 146 | 103 | 26 | 102 | 129 |
| 54 | 45 | 133 | 77 | 137 | 13 | 19 | | 27 |
| 47 | 59 | 76 | 2 | 134 | 17 | 22 | | 25 |
| 46 | 60 | 75 | 143 | 18 | | | | |
| 48 | 63 | 74 | | 4 | | | | |
| | | 73 | | | | | | |

**Table A6. 24 Policy 5 - 40%**

| Loader 1 | Loader 2 | Loader 3 | Loader 4 | Loader 5 | Loader 6 | Loader 7 | Loader 8 | Loader 9 |
|---|---|---|---|---|---|---|---|---|
| 54 | 4 | 55 | 3 | 56 | 106 | 65 | 151 | 141 |
| 52 | 21 | 48 | 12 | 61 | 104 | 67 | 83 | 146 |
| 51 | 134 | 46 | 14 | 62 | 103 | 68 | 152 | 145 |
| 50 | 136 | 40 | 17 | 69 | 129 | 85 | 133 | 102 |
| 101 | 137 | 36 | 19 | 87 | 41 | 86 | 96 | 78 |
| 142 | 140 | 38 | 13 | 118 | 126 | 154 | 1 | 97 |

| Loader 1 | Loader 2 | Loader 3 | Loader 4 | Loader 5 | Loader 6 | Loader 7 | Loader 8 | Loader 9 |
|---|---|---|---|---|---|---|---|---|
| 2 | 139 | 37 | 26 | 63 | 127 | 91 | 95 | 53 |
| 143 | 135 | 24 | 29 | 64 | 119 | 90 | 131 | 98 |
| 144 | 49 | 25 | 30 | 125 | 155 | 92 | 124 | 72 |
| 10 | 8 | 27 | 31 | 44 | 120 | 89 | 123 | 73 |
| 33 | 22 | 38 | 32 | 5 | 121 | 88 | 7 | 79 |
| 23 | 18 | 39 | | 43 | 122 | 84 | 132 | 80 |
| 35 | 16 | 58 | | 42 | 116 | 66 | 94 | 81 |
| 34 | | | | 45 | 115 | 100 | 93 | 150 |
| 47 | | | | 59 | 112 | 75 | 76 | 148 |
| | | | | 60 | 128 | 99 | 77 | |
| | | | | 57 | | 70 | 74 | |
| | | | | | | 71 | 82 | |

**Table A6. 25 Policy 6 - 40%**

| Loader 1 | Loader 2 | Loader 3 | Loader 4 | Loader 5 | Loader 6 | Loader 7 | Loader 8 | Loader 9 |
|---|---|---|---|---|---|---|---|---|
| 55 | 69 | 72 | 34 | 137 | 16 | 33 | 142 | 24 |
| 61 | 68 | 50 | 35 | 134 | 21 | 144 | 101 | 23 |
| 56 | 85 | 36 | 38 | 12 | 140 | 8 | 10 | 78 |
| 57 | 84 | 37 | 28 | 112 | 145 | 49 | 29 | 80 |
| 62 | 100 | 41 | 43 | 123 | 94 | 135 | 32 | 83 |
| 68 | 99 | 42 | 5 | 124 | 132 | 136 | 31 | 92 |
| 67 | 70 | 125 | 44 | 151 | 7 | 139 | 30 | 95 |
| 66 | 97 | 64 | 118 | 80 | 122 | 81 | 128 | 155 |
| 71 | 52 | 87 | 93 | | 121 | 82 | 154 | 119 |
| 65 | 51 | 86 | 1 | | 115 | 131 | 91 | 127 |
| 98 | 40 | 89 | 96 | | 104 | 120 | 79 | 126 |
| 53 | 39 | 88 | 152 | | 103 | 26 | 102 | 129 |
| 54 | 45 | 133 | 77 | | 13 | 19 | | 27 |
| 47 | 59 | 76 | 2 | | 17 | 22 | | 25 |
| 46 | 60 | 75 | 143 | | | | | |
| 48 | 63 | 74 | | | | | | |
| | | 73 | | | | | | |

**Table A6. 26 Policy 7 - 40%**

| Loader 1 | Loader 2 | Loader 3 | Loader 4 | Loader 5 | Loader 6 | Loader 7 | Loader 8 | Loader 9 |
|---|---|---|---|---|---|---|---|---|
| 54 | 4 | 55 | 3 | 56 | 106 | 65 | 151 | 102 |
| 52 | 21 | 48 | 12 | 61 | 104 | 67 | 83 | 78 |
| 51 | 134 | 46 | 14 | 62 | 103 | 68 | 152 | 97 |
| 50 | 136 | 40 | 17 | 69 | 129 | 85 | 133 | 53 |
| 101 | 137 | 36 | 19 | 87 | 41 | 86 | 96 | 98 |
| 142 | 140 | 38 | 13 | 118 | 126 | 154 | 1 | 72 |
| 2 | 139 | 37 | 26 | 63 | 127 | 91 | 95 | 73 |
| 143 | 135 | 24 | 29 | 64 | 119 | 90 | 131 | 79 |
| 144 | 49 | 25 | 30 | 125 | 155 | 92 | 124 | |

| Loader 1 | Loader 2 | Loader 3 | Loader 4 | Loader 5 | Loader 6 | Loader 7 | Loader 8 | Loader 9 |
|---|---|---|---|---|---|---|---|---|
| 10 | 8 | 27 | 31 | 44 | 120 | 89 | 123 | |
| 33 | 22 | 38 | 32 | 5 | 121 | 88 | 7 | |
| 23 | 18 | 39 | | 43 | 122 | 84 | 132 | |
| 35 | 16 | 58 | | 42 | 116 | 66 | 94 | |
| 34 | | | | 45 | 115 | 100 | 93 | |
| 47 | | | | 59 | 112 | 75 | 76 | |
| | | | | 60 | 128 | 99 | 77 | |
| | | | | 57 | | 70 | 74 | |
| | | | | | | 71 | 82 | |

# Appendix A7 – Simulation and Economic Analysis

## *A7.1 Cost to Operate Frame Loader*

This machine does not exist. The commercial machine with similar capabilities is a compactor that compacts a load of MSW into a cube and inserts it walking floor van trailer. The capabilities, and thus the cost, of this compactor exceeds the requirement for a machine that compresses four round bales into a 2.4m wide x 2.7m high cross-section.

This cost analysis is based on a hypothesized machine that is trailer mounted with a 50-kw diesel engine to power the needed hydraulics. The frame to be loaded will lock onto attachment points which secure it to the frame loader. The SSL forklift (Appendix A7.3) will place the empty frame in place and remove the loaded frame.

| | |
|---|---|
| Purchase Price: | \$30,000 |
| Design life: | 6,000 h |
| Annual use: | 10 h/d, 5 d/wk, 50 wk/y = 2500 h/y |
| Interest rate: | 8%  r = 0.08 |
| Insurance rate: | 0.25% |
| Tax rate: | 1% |
| Repair and maintenance factor (R/M) | \$1.50/h |
| Fuel use: | 3 liter/h |
| Fuel cost: | \$0.74/liter |
| Labor cost (including benefits): | \$15/h |
| Expected service: | $n = \frac{6{,}000\text{ h}}{2500\text{ h/y}} = 2.4\text{ y}$ |
| Salvage value | 10%  $S_v = 0.1$ |

Ownership cost:

Ownership cost percentage (ASABE, 2006):

$$C_o = \frac{1-S_v}{n} + \frac{(1+S_v)r}{2} + K_2$$

where $C_o$ = ownership cost percentage (dec),
$S_v$ = salvage value (dec),
n = machine life (y),
r = interest rate (dec), and
$K_2$ = factor for taxes and insurance (dec).

$K_2 = 0.01 + 0.0025 = 0.0125$

$$\begin{aligned} C_o &= \frac{1-0.1}{2.4} + \frac{(1+0.1)(0.08)}{2} + 0.0125 \\ &= 0.375 + 0.044 + 0.0125 \\ &= 0.4315 \end{aligned}$$

Annual ownership cost ($):

$30,000 x 0.4315 = $12,945

Annual ownership cost ($/h):

$$\frac{\$12{,}945}{2500\text{ h}} = \$5.18/\text{h}$$

Operating Cost ($/h):

| | | | | | | |
|---|---|---|---|---|---|---|
| R/M | + | Fuel | + | Labor | = | Total |
| 1.50 | + | 3 x 0.74 | + | 15 | = | $18.72/h |

Total cost ($/h):

| | | | | |
|---|---|---|---|---|
| Ownership | + | Operating | = | Total |
| 5.18 | + | 18.75 | = | $23.93/h |

Each frame holds 5.55 dry Mg and the grapple loader loads 30 frames/d.

5.55 dry Mg/frame x 30 frames/d = 166.6 dry Mg/d

$$\frac{10\ \text{h/d x } \$23.93/\text{h}}{166.6\ \text{dry Mg/d}} = \$1.44/\text{dry Mg}$$

## *A7.2 Cost to Operate SSL Forklift*

Machine selected for this study
Taylor Model TX 360M

| | |
|---|---|
| Purchase Price: | \$154,400 |
| Design life: | 15,000 h |
| Annual use: | 5 h/d, 5 d/wk, 50 wk/y = 1250 h |
| Interest rate: | 8%  r = 0.08 |
| Insurance rate: | 0.25% |
| Tax rate: | 1% |
| Repair and maintenance factor (R/M) | \$3.00/h |
| Fuel use: | 12 liter/h |
| Fuel cost: | \$0.74/liter |
| Labor cost (including benefits): | \$15/h |

Expected service:

$$n = \frac{15{,}000\ \text{h}}{1250\ \text{h/y}} = 12\ \text{y}$$

Salvage value  10%  $S_v = 0.1$

Ownership cost:

Ownership cost percentage (ASABE, 2006):

$$C_o = \frac{1 - S_v}{n} + \frac{(1 + S_v)r}{2} + K_2$$

where $C_o$ = ownership cost percentage (dec),
$S_v$ = salvage value (dec),
n = machine life (y),
r = interest rate (dec), and
$K_2$ = factor for taxes and insurance (dec).

$K_2 = 0.01 + 0.0025 = 0.0125$

$$C_o = \frac{1-0.1}{12} + \frac{(1+0.1)(0.08)}{2} + 0.0125$$
$$= 0.075 + 0.044 + 0.0125$$
$$= 0.1315$$

Annual ownership cost ($):

$154,400 x 0.1315 = $20,304

Annual ownership cost ($/h):

$$\frac{\$20{,}304}{1250} = \$16.24/\text{h}$$

Operating Cost ($/h):

| R/M | + | Fuel | + | Labor | = | Total |
|---|---|---|---|---|---|---|
| 3 | + | 12 x 0.74 | + | 15 | = | $26.88/h |

Total cost ($/h):

| Ownership | + | Operating | = | Total |
|---|---|---|---|---|
| 16.24 | + | 26.88 | = | $43.12/h |

## *A7.3 Cost to Operate Unloader*

Machine selected for this study
Taylor Model TX 360M Forklift

| | |
|---|---|
| Purchase Price: | \$154,400 |
| Design life: | 15,000 h |
| Annual use: | 24 h/d, 7 d/wk, 50 wk/y = 8400 h |
| Interest rate: | 8% $r = 0.08$ |
| Insurance rate: | 0.25% |
| Tax rate: | 1% |
| Repair and maintenance factor (R/M) | \$3.00/h |
| Fuel use: | 12 liter/h |
| Fuel cost: | \$0.74/liter |
| Labor cost (including benefits): | \$15/h |

Expected service:

$$n = \frac{15{,}000\ \text{h}}{8400\ \text{h/y}} = 1.78\ \text{y}$$

Salvage value 10% $S_v = 0.1$

Ownership cost:

Ownership cost percentage (ASABE, 2006):

$$C_o = \frac{1 - S_v}{n} + \frac{(1 + S_v)r}{2} + K_2$$

where $C_o$ = ownership cost percentage (dec),
$S_v$ = salvage value (dec),
n = machine life (y),
r = interest rate (dec), and
$K_2$ = factor for taxes and insurance (dec).

$K_2 = 0.01 + 0.0025 = 0.0125$

$$
\begin{aligned}
C_o &= \frac{1-0.1}{1.78} + \frac{(1+0.1)(0.08)}{2} + 0.0125 \\
&= 0.506 + 0.044 + 0.0125 \\
&= 0.5625
\end{aligned}
$$

Annual ownership cost ($):

$154,400 x 0.5625 = $86,850

Annual ownership cost ($/h):

$$\frac{\$86{,}850}{8400} = \$10.34/\mathrm{h}$$

Operating Cost ($/h):

| R/M | + | Fuel | + | Labor | = | Total |
|---|---|---|---|---|---|---|
| 3 | + | 12 x 0.74 | + | 15 | = | $26.88/h |

Total cost ($/h):

| Ownership | + | Operating | = | Total |
|---|---|---|---|---|
| 10.34 | + | 26.88 | = | $37.22/h |

## *A7.4 Arena VBA code*

```
Public xl As Excel.Application
Public xb As Excel.Workbook
Public xs As Excel.Worksheet
Public s As SIMAN
Public m As Model
Public FileToUse As String
Public i As Integer

Private Sub ModelLogic_RunBeginSimulation()
FileToUse = "D:\PhD-beast\Data\M6_40.xls"

Set xl = GetObject("", "Excel.Application")
xl.Workbooks.Open FileToUse
xl.Visible = True
i = 2
Set xlb = xl.Workbooks("M6_40.xls")
Set s = ThisDocument.Model.SIMAN

'Code to set min, max and mode weigh time
s.VariableArrayValue(s.SymbolNumber("minWeighTime")) = 0.5
s.VariableArrayValue(s.SymbolNumber("WeighTime")) = 1
s.VariableArrayValue(s.SymbolNumber("maxWeighTime")) = 1.5

'Code to set min, max and mode unload times
s.VariableArrayValue(s.SymbolNumber("minUnloadTime")) = 5
s.VariableArrayValue(s.SymbolNumber("UnloadTime")) = 10
s.VariableArrayValue(s.SymbolNumber("maxUnloadTime")) = 15

'Code to set min, max and mode load times
s.VariableArrayValue(s.SymbolNumber("minloadTime")) = 30
s.VariableArrayValue(s.SymbolNumber("loadTime")) = 40
s.VariableArrayValue(s.SymbolNumber("maxloadTime")) = 45

'Code to set min, max and mode process times
s.VariableArrayValue(s.SymbolNumber("minProcessTime")) = 16.14
s.VariableArrayValue(s.SymbolNumber("ProcessTime")) = 17.14
s.VariableArrayValue(s.SymbolNumber("maxProcessTime")) = 18.14


End Sub

Private Sub ModelLogic_RunEndSimulation()
xl.Quit
```

```
End Sub

Private Sub VBA_Block_1_Fire()
Set xb = xl.Workbooks("M6_40.xls")
Dim temp As Long
'Code for Loader 1
Set xs = xb.Worksheets("Loader 1")
xs.Activate
temp = xs.Cells(i, 3)

s.VariableArrayValue(s.SymbolNumber("L1Time")) = xs.Cells(i, 3)
s.VariableArrayValue(s.SymbolNumber("DL1")) = xs.Cells(i, 5)
s.ResourceCapacity(s.SymbolNumber("Truck1")) = xs.Cells(i, 6)

'Code for Loader 2
Set xs = xb.Worksheets("Loader 2")
xs.Activate
s.VariableArrayValue(s.SymbolNumber("L2Time")) = xs.Cells(i, 3)
s.VariableArrayValue(s.SymbolNumber("DL2")) = xs.Cells(i, 5)
s.ResourceCapacity(s.SymbolNumber("Truck2")) = xs.Cells(i, 6)


'Code for Loader 3
Set xs = xb.Worksheets("Loader 3")
xs.Activate
s.VariableArrayValue(s.SymbolNumber("L3Time")) = xs.Cells(i, 3)
s.VariableArrayValue(s.SymbolNumber("DL3")) = xs.Cells(i, 5)
s.ResourceCapacity(s.SymbolNumber("Truck3")) = xs.Cells(i, 6)


'Code for Loader 4
Set xs = xb.Worksheets("Loader 4")
xs.Activate
s.VariableArrayValue(s.SymbolNumber("L4Time")) = xs.Cells(i, 3)
s.VariableArrayValue(s.SymbolNumber("DL4")) = xs.Cells(i, 5)
s.ResourceCapacity(s.SymbolNumber("Truck4")) = xs.Cells(i, 6)


'Code for Loader 5
Set xs = xb.Worksheets("Loader 5")
xs.Activate
s.VariableArrayValue(s.SymbolNumber("L5Time")) = xs.Cells(i, 3)
s.VariableArrayValue(s.SymbolNumber("DL5")) = xs.Cells(i, 5)
s.ResourceCapacity(s.SymbolNumber("Truck5")) = xs.Cells(i, 6)
```

```
'Code for Loader 6
Set xs = xb.Worksheets("Loader 6")
xs.Activate
s.VariableArrayValue(s.SymbolNumber("L6Time")) = xs.Cells(i, 3)
s.VariableArrayValue(s.SymbolNumber("DL6")) = xs.Cells(i, 5)
s.ResourceCapacity(s.SymbolNumber("Truck6")) = xs.Cells(i, 6)


'Code for Loader 7
Set xs = xb.Worksheets("Loader 7")
xs.Activate
s.VariableArrayValue(s.SymbolNumber("L7Time")) = xs.Cells(i, 3)
s.VariableArrayValue(s.SymbolNumber("DL7")) = xs.Cells(i, 5)
s.ResourceCapacity(s.SymbolNumber("Truck7")) = xs.Cells(i, 6)


'Code for Loader 8
Set xs = xb.Worksheets("Loader 8")
xs.Activate
s.VariableArrayValue(s.SymbolNumber("L8Time")) = xs.Cells(i, 3)
s.VariableArrayValue(s.SymbolNumber("DL8")) = xs.Cells(i, 5)
s.ResourceCapacity(s.SymbolNumber("Truck8")) = xs.Cells(i, 6)


'Code for Loader 9
Set xs = xb.Worksheets("Loader 9")
xs.Activate
s.VariableArrayValue(s.SymbolNumber("L9Time")) = xs.Cells(i, 3)
s.VariableArrayValue(s.SymbolNumber("DL9")) = xs.Cells(i, 5)
s.ResourceCapacity(s.SymbolNumber("Truck9")) = xs.Cells(i, 6)


i = i + 1

End Sub
```