A Computer Simulation Model for Predicting the Impacts of Log Truck Turn-Time on Timber Harvesting System Productivity

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(ABSTRACT)

A computer simulation model was developed to represent a logging contractor's harvesting and trucking system of wood delivery from the contractor's in-woods landing to the receiving mill. The Log Trucking System Simulation model (LTSS) focuses on the impacts to logging contractors as changes in truck turn times cause an imbalance between harvesting and trucking systems. The model was designed to serve as a practical tool that can illustrate the magnitude of cost and productivity changes as the delivery capacity of the contractor's trucking system changes.

The model was used to perform incremental analyses using an example contractor's costs and production rates to illustrate the nature of impacts associated with changes in the contractor's trucking system. These analyses indicated that the primary impact of increased turn times occurs when increased delivery time decreases the number of loads per day the contractor's trucking system can deliver. When increased delivery times cause the trucking system to limit harvesting production, total costs per delivered ton increase. In cases where trucking significantly limits system production, total costs per delivered ton would decrease if additional trucks were added.

The model allows the user to simulate a harvest with up to eight products trucked to different receiving mills. The LTSS model can be utilized without extensive data input requirements and serves as a user friendly tool for predicting cost and productivity changes in a logging contractor's harvesting and trucking system based on changes in truck delivery times.

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CHAPTER 1 INTRODUCTION

1.1 Background Information and Study Objective

In the Southeastern United States independent logging contractors typically supply the wood to forest products mills. The independent logging contractors are responsible for felling and preparing the trees, transporting them to a concentration point, or in-woods landing, and then loading and trucking to the consuming mill (Shaffer and Walbridge, 1990). The balanced operation of the logging contractor's trucking and harvesting systems is essential for the system to operate efficiently. Storage capacities for wood at the logging contractor's in woods landing are often limited. In order to continue operating efficiently a contractor must have sufficient trucking capacity to deliver wood from the harvest site to the mill in a timely manner to avoid running out of product storage space at the landing.

In this typical wood supply system; wood is transported, or "skidded" from the in-woods harvesting operation to the loader at the landing where multiple products may be merchandised and trucked to different receiving mills. Trucks are loaded at the in-woods landing. The loaded truck is driven to the consuming mill, or to a concentration yard, where it crosses the scales to determine gross vehicle weight. Next, the truck is driven into the mill where the unloading equipment removes the load of wood. After being unloaded the truck re-crosses the scales to determine the amount of payload the truck was carrying. Afterwards, if time permits, the empty truck returns to the in-woods landing for another load of wood.

The total round trip delivery time for a truck in a logging contractor's trucking system includes time spent getting loaded at the in-woods landing, driving loaded to the mill, unloading time or turn time at the mill, and returning empty to the in-woods landing. Delays, or increased time spent at any point in this round trip process can decrease the total number of loads per day a trucking fleet is capable of delivering.

Independent loggers are paid on a production basis, and the ultimate measure of their production is the amount of wood delivered to the mill. When the contractor's trucking system is not capable of keeping up with the in-woods production, the in woods landing area may fill and production must halt (McCormack, 1990); ultimately limiting production of the entire system to the delivery capacity of the trucking fleet.

Much attention has been focused on predicting production rates from the in-woods harvesting system, although trucking capacity can often be a limiting factor. A survey of West Virginia loggers indicated that trucking is one of the most frequently cited production limiting factors, especially for smaller producers (Luppold et al., 1998).

Several "tree to mill" forest harvesting computer models created over the years have been oriented towards predicting the system production and machine productivity rates within the harvesting system, or directed towards predicting the interaction between stand characteristics and machine productivity. Most of the models were complex and required extensive amounts of data collection for each piece of harvesting equipment or for stand and site characteristics of the tract being harvested. Many of the models were difficult to learn to use and cumbersome in their data requirements (Goulet, et al. 1979). Changes in productivity based on trucking capacity were not the focus of the models.

Whenever a log truck spends more time at the contractor's in-woods landing, at the receiving mill, en-route to the mill, or when a logging contractor is moved to a new harvest location, the total round trip truck turn time will change. Changes in the total round trip time affect the number of loads of wood per day a trucking fleet can deliver and can lead to an imbalance between the trucking system and harvesting systems. Yet, there is often no easy way to quantify the magnitude of impacts to the logging contractor's harvesting and trucking system as truck delivery times change.

Imbalances between a logging contractor's trucking and harvesting systems can occur when changes in the round trip trucking times change the delivery capacity of the contractor's trucking system. The objective of this investigation was to develop a generalized computer simulation model that can be used as a practical tool to illustrate the impacts that truck turn times have on the productivity of independent logging contractors. The model was built at a generalized level so that it can be easily utilized and can predict the magnitude of impacts without requiring excessive amounts of data collection for the user to operate the model.

CHAPTER 2 LITERATURE REVIEW

2.1 StellaÒ Systems Modeling Software

The systems modeling software Stella® Research version 6.0 was used to create the model for this project. Stella® is a package of systems modeling software developed by High Performance Systems Incorporated. H.P.S. Inc. produces two versions of this modeling software, Stella® and ithink®. The software allows the modeler to develop an interface to facilitate the model's use and illustrate key features for the model user. The generic model building structures used within the Stella® environment make the modeling software adaptable to many fields of study and it has been used in the fields of math, engineering, physical sciences, life sciences, social sciences, and the humanities (HPS Inc., 2000a).

2.2 Previous Forest Harvesting Computer Simulation Models

Considerable research has been conducted using computers for analyzing and simulating forest harvesting systems. Most of the research has focused on one of three categories: models representing entire harvesting and transportation systems from the tree to the mill, models representing one or two machines within a harvesting system, and spreadsheet-based harvesting system cost estimators.

2.2.1 Complete Wood Production Systems or Tree to Mill Simulators

Some of the earliest work in harvesting system modeling and one of the most widely used models (Wang et al., 1998) was the Harvesting Analysis Technique (HAT). HAT was a result of work begun in the 1960's by the American Pulpwood Association's Harvesting Research Project. The HAT is a combination of three different computer models. The forest stand is represented using a previously mapped stand or a map generated using a stand simulator. Individual machines are modeled using a generalized machine simulator

GENMAC. The Harvesting Systems Simulator program is used to simulate the interactions among the machines within the system.

GENMAC uses the locations of trees in the mapped stand along with detailed input on the machine functions and productivity rates to determine production rates from a particular machine in a simulated stand of trees. Production rate outputs for individual machines from GENMAC can be used as inputs to the HSS, which simulates the interactions of machines within the harvesting system (Stuart, 1981). While the main outputs from the HSS relate to machine productivity of the harvesting system, it is a tree to mill harvesting simulator. Estimates of trucking production are based on distributions of driving times over improved and unimproved roads, as well as return times from the mill (Goulet et al., 1979).

Goulet et al. (1979) offered a summary of the major tree to mill forest harvesting simulation models created up to that date, including the HSS described by Stuart (1981) in the HAT. They were:

> Auburn Pulpwood Harvesting System Simulator (APHSS) (1969)
> The APHSS is a simulation model of production and transportation in southeastern pulpwood harvesting systems. The model is deterministic and uses average cycle times as inputs to drive the system operations. For the simulated stand the model assumes an unlimited number of identical trees are available for harvesting by the machines in the system. Trucking production was predicted using an average time that covered all of the activities involved in the round trip delivery of wood to the mill. Outputs include production rates and costs per log.
>
> Forest Harvesting Simulation Model (FHSM) (1975)
> FHSM was designed as a model that could be flexible enough to simulate many different harvesting systems while at the same time containing enough detail so that individual sections of the harvesting system can be analyzed. A detailed database including stand data, time study data or probability distributions for

various functions are required. Transportation of wood to the mill is based on average drive times over improved and unimproved roads and distributions of times for scaling and unloading at the mill. Outputs include production rates for equipment and total wood delivered to the mill.

Full-Tree Chipping and Transport Simulator (FCTS) (1976)

The FCTS is a combination of two General Purpose Simulation System (GPSS) simulation models, one model of a full tree harvesting and chipping system, and the other of a trucking system. The model requires detailed inputs, including distributions of times for each component of the trucking process. Inputs required for the harvesting system model including tree location, volume, and the order in which the tree is harvested. Outputs include cost and production averages for each piece of equipment.

Georgia Tech Model (1968)

The Georgia Tech model, one of the first harvesting system simulation models, modeled production of shortwood pulpwood in the southern U.S. The model has 28 configurations for pulpwood producers operations and requires inputs on 19 variables and 15 distribution parameters to characterize the harvesting system. Trucking delivery is modeled using distributions of values for hauling time over improved and unimproved roads as well as unloading time at the mill. Outputs include average production of the system.

Residues for Power (REPO) (1976)

The REPO model was designed to evaluate systems for moving harvesting residues in the form of chips to a simulated power plant. In the model, materials flow from one operation to the next throughout the course of a workday. Although not originally designed to model timber harvesting systems it can be adapted to represent harvesting and transportation of timber.

Simulation Applied to Logging Systems (SAPLOS) (1973)

SAPLOS is a discrete-event harvesting system simulation model. It is a flexible model that can simulate many different types of harvesting operations. Inputs include system cost and setup data, and in addition the user must write two programs to describe tree characteristics, stand topography and distance characteristics. Outputs include cost and production of the system as a whole and for each individual activity.

Timber Harvesting and Transport Simulator (THATS) (1975)

The THATS model is a FORTRAN based simulation model that represents common harvesting system operations. Inputs are in the form of system cost components, data for trees in the stand to be harvested, along with averages and standard deviations for the harvesting functions. Truck transportation is predicted based on inputs for distributions of hauling times to the mill, unloading time at the mill, and the return trip. The final output gives a basic production table that can be used to create desired variables.

By examining the previously described models Goulet et. al. concluded that there was no general consensus regarding the major factors to be included in a harvesting system model. Additionally, the data requirements in time and productivity studies required for model inputs would generally be very time consuming to gather (Goulet et al., 1979).

Another model, the Harvesting System Analyzer is a two-part program developed by the Tennessee Valley Authority. Input for the first program includes information about each machine in the system. Outputs from the first part include a summary of the input data plus the computed fixed and operating costs for the machinery. The second part requires input information on the machines from the first program, along with stand information, to predict costs and length of time required for harvesting the specified stand. Outputs include details on the stand harvested, performance of each machine as well as total system performance (Reisinger et al., 1986).

More recent work in harvesting system simulation includes a stochastic Ground Based harvesting simulation model (GB-SIM) developed to estimate stump to truck production in Appalachian hardwoods. The model focuses on system productivity and product yields. The model requires considerable inputs for system production (cycle times, skidding distances, etc.), stand characteristics, costs, and product assortment and yields. Outputs are related to machine and system production rates and product yields (Baumgras et al., 1993).

A computer simulation model was developed that models the interaction of stand characteristics, type of harvest conducted, and machines used in the harvesting system. The user performs the simulation by moving machines in the simulated stand on the computer screen. At the conclusion of the simulation, outputs are provided on machine productivity and the condition of the residual stand (Wang and Greene, 1999).

2.2.2 Spreadsheet Based Cost Estimators

Reisinger et al. (1986) summarized several spreadsheet based programs for analyzing harvesting operations. They were:

Auburn Harvesting Analyzer (AHA) (1985)
The AHA uses stand volume and stocking information along with regression equations to predict a particular system's harvesting production rate. Other inputs include cost of the machinery as well as road building costs and quota restrictions. Outputs summarize system balance, as well as machine productivity for each function.

Logging Cost Analysis Package (LCAP) (1984)
The LCAP was developed at North Carolina State University. LCAP estimates harvesting system costs based on the machine rate method. Inputs include costs of machinery, labor, and other operating costs. Outputs include system costs per hour, day, month, or year.

Program for Logging Cost Estimation (PROLOG) (1982)
PROLOG was originally developed for teaching at the University of Georgia. PROLOG inputs include general assumptions about the harvesting system, equipment and labor costs. Outputs included summaries of equipment cost, whole system costs, and a summary of the system setup (Reisinger et al., 1986).

Tree Harvesting Simulator (TREESIM) (1986)
TREESIM is a spreadsheet based harvesting cost and productivity analyzer, built on the foundation of the Auburn Harvesting Analyzer. Developed by Caterpillar's research department, TREESIM uses stand data along with equipment and financial data to estimate costs and productivity of the harvesting system being analyzed. Inputs include productivity data for machines in the system, costs of owning and operating the machinery, information on the stand being harvested, and information on the business's overhead costs. Outputs include measures of system balance, productivity, and financial data for the system. Once data for a harvesting system has been entered, TREESIM allows for quick sensitivity analyses of system variables (Dremann, 1986).

2.2.3 One or Two Machine Simulation Models

A stochastic model was developed to simulate a rubber-tired feller-buncher. Model inputs include stand characteristics such as average DBH, tree height, trees per acre, and volume per acre, along with characteristics of the feller-buncher. Outputs include productive time worked, trees per hour, cycles per hour, and average number of trees per bunch (Winsauer and Bratley, 1982).

Another model was developed that can use outputs from the feller-buncher model (Winsauer and Bratley, 1982) to perform a simulation of a grapple skidder and whole-tree chipper combination. This model simulates the interaction of the two machines using bunch sizes from the previous run of the feller-buncher simulation, stand data on average

DBH in the stand, and machine information for the skidder and chipper. Outputs show production data for the skidder and chipper (Winsauer, 1982).

Computer simulation models have been used to design and evaluate new machine concepts at less cost than actual field-testing or construction of a prototype. A computer animation model of a feller-buncher was created where the user controlled the feller-buncher through the use of knobs and buttons. The user fells and stacks trees from a simulated forest and at the end of the simulation a report is generated giving the condition of the simulated forest as well as locations and contents of the bunches produced by the feller-buncher (Block and Fridley, 1990).

An interactive computer aided simulation was used in the design process for a feller buncher intended for use on steep terrain. The model used diameter and location data from a stand to be thinned along with machine specifications to aid in the design and evaluation of the feller-buncher (Fridley et al., 1988).

A computer simulation program was used to predict the interaction of stand factors, such as DBH and distance between trees, and the effects associated with different operating patterns on feller buncher productivity (Greene et al., 1987).

A computer simulation that modeled harvesting equipment in a variety of harvest types, was used along with another computer program to estimate damage to residual trees from a partial cutting operation (Bragg et al., 1994).

Aedo-Ortiz et. al. (1997) developed a simulation model of a harvester/forwarder system for thinning softwoods in the Pacific Northwest. The model tracked the flow of materials during the harvesting and processing steps and special attention was focused on the effectiveness of using statistical distributions from field studies.

2.3 Trucking Studies

Computer software has been developed for log truck scheduling to optimize trucking fleets and to minimize delays that occur at the receiving mill from unscheduled truck arrivals. A network programming approach was used for scheduling dispatches of trucks from a centralized trucking fleet based at the receiving mill. Trucks travel from the central location to multiple landings to receive wood and transport it to the mill. Scheduling was designed to optimize a delivery schedule at the mill and minimize trucking costs (Shen and Sessions, 1989).

Another log truck-scheduling program based on a simulation process was also designed to optimize delivery of wood from a centralized fleet of trucks. Truck scheduling attempted to coordinate deliveries of different products to meet demand at different mill locations and optimize truck arrivals at the mills to avoid excessive delays at the receiving mill. The truck-scheduling program was implemented by some of the largest forest products companies in Chile (Weintraub, et. al., 1996).

The Forest Engineering Research Institute of Canada (FERIC) has directed research toward computer simulation of trucks and trucking systems. A study was performed using a computer simulation model to determine the optimal sizing of log trucks and to predict the costs and productivity of three different hauling options (Oakley and Marshall, 1989). Another simulation program was developed that evaluated truck productivity and fuel consumption for different types of trucks, based on driving technique and type of road the truck traveled over (Nader and Jalinier, 1993).

CHAPTER 3 BUILDING THE MODEL

3.1 Model Components

The systems modeling software Stella® 6.0 (HPS Inc. 2000a) was used to create a model of an independent logging contractor's wood supply system. The Log Trucking System Simulation Model (LTSS) is a generalized representation of a typical southern logging contractor's operation from the in-woods landing to the receiving mill or concentration yard. In this typical operation, wood is skidded to the contractor's landing from an in-woods harvesting crew. The contractor's trucks arrive at the landing, pull up to the loader to receive their load, and then drive to the receiving mill to deliver their load. The LTSS model represents truck delivery of wood from the contractor's landing to the receiving mill(s) based on availability of wood at the landing, production rates at the landing, and round trip delivery times.

The basic building blocks upon which models are constructed in the Stella® modeling environment (Figure 3.1) include stocks, flows, converters, and connectors (arrow).

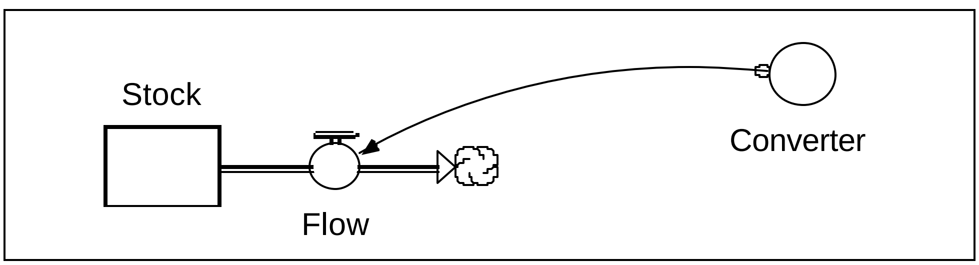

Figure 3.1 Main components of Stella® models.

Stocks represent accumulations or physical stocks within the system, such as total wood in the stand, or inventories of wood on the landing. Flows are the way in which stocks are filled and drained. For example wood moves from a stack of inventoried wood (stock) on the landing to a waiting truck, through the "flow" of loading. Converters can hold variable values and can be used to turn inputs into outputs. In the LTSS model, one use of converters is to convert turn times that are input as minutes into the equivalent number of hours for use in the model flows. Connectors link related parts of the model and transmit values within the model (HPS Inc., 2000b). For example, connectors are used in the LTSS model to link the flow of “Loading” and the stock of “Trucks available to use”. When no trucks are available to use, the flow of loading wood onto trucks cannot occur.

The primary components of the LTSS model are displayed in Figure 3.2. The actual model layout (Appendix A) is more complicated and visually confusing as result of additional model building blocks used to track and regulate system flows.

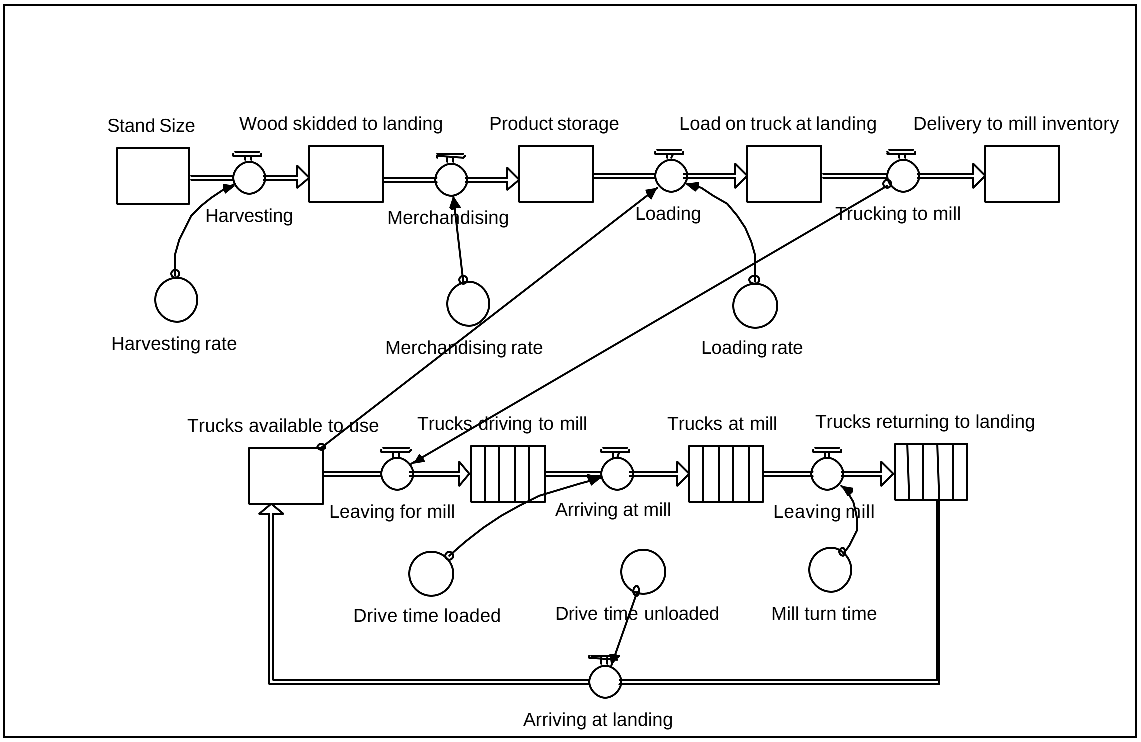

Figure 3.2 Basic organization of the LTSS model.

3.2 Assumptions Made in the Model

Simulations with the LTSS model represent truck transportation of wood from a logging contractor’s landing to the receiving mill(s). Because of the focus of this study on the impacts to logging contractors as a result of changes in their trucking system, no attempt was made to model the activities of the in-woods harvesting crew. Wood flow in the model begins with a specified number of tons of wood in a stand available for harvest. An assumption was made that wood is skidded to the landing from the harvesting operation at a known constant rate of production specified by the user. At the landing, wood is processed and inventoried if no trucks are available. If trucks are available at the landing, wood is loaded onto trucks and the contractor's trucking system delivers wood from the landing to the receiving mill(s).

The contractor's in-woods landing has a limited amount of storage capacity to inventory wood while waiting for trucks to transport wood to the mill. Harvesting production in the model continues at the specified harvesting rate for the contractor's entire scheduled workday unless the amount of wood inventoried at the landing reaches maximum storage capacity. If the landing storage area reaches maximum capacity, potential harvesting production is lost, as the harvesting crew remains idle until more storage is available at the landing. When storage at the landing is not a constraint, the harvesting crew is utilized for the entire scheduled workday. The contractor's average total system production per day cannot increase above the harvesting production rate per hour $\times$ number of scheduled hours per day, but can decrease as bottlenecks in the trucking system cause the landing's maximum capacity to be reached and harvesting production decreases. An assumption was made that the contractor would continue producing for the number of days required to complete the stand harvest and no allowance was made for other imposed production restrictions such as mill quotas.

An assumption was made that the amount of wood in the stand represents merchantable wood available for harvest and no allowance is made for non-merchantable wood in the stand. The total amount of wood in the stand represents wood that will be skidded to a single in-woods landing. If the model user wishes to simulate an actual stand harvest where multiple in-woods landings would be utilized, multiple simulations can be performed where the total wood skidded to each landing is represented by a separate stand harvest.

The amount of wood available for harvest can be composed of up to eight product types. For each product type, different average truck payloads as well as mill turn times and drive times to and from the mill can be specified. The specified product percentages assume an equal distribution of products throughout the stand. Wood flows onto the landing in the same percentages as specified for the stand as a whole. Once wood is skidded to the landing, the loader processes the wood through the function of "merchandising", to prepare it for loading on a truck. Merchandising can include such processes as removing limbs and measuring and cutting logs to an appropriate length in order to maximize revenues for different markets. The categories for product types on the model control panel represent product sorts common in the Appalachian region. However the specific product names are only labels for tracking the amount of wood in each category as it flows through the contractor's system and the categories can represent any product type the user wishes. The percentage of products in the stand assumes the user classified the products based on the highest value for each product use. An assumption was made that only one product type will be loaded on each truck. After being harvested and processed at the landing, inventories of each product remain distinct and will only be loaded on a truck going to the appropriate mill destination.

Once the loader processes wood that has been skidded to the landing, if a truck is not available, the loader stacks the wood in inventory on the landing. If a truck is available at the landing, the product is loaded onto the truck until the payload limit for that truck is reached. The model represents an operation with a single loader where loading trucks takes priority. While a truck is being loaded, merchandising stops because the loader cannot perform two tasks at the same time. Wood is first loaded onto the waiting truck from inventory on the landing. If there is not enough product inventoried at the landing to complete the truck load, inventoried wood is loaded first, then the loader begins alternating the processes of merchandising wood as it arrives on the landing and then loading wood onto the waiting truck.

The model user specifies the number of trucks available to use in the contractor's trucking system. When a stand harvest begins, all trucks are available at the landing. The total round trip time per truckload of wood delivered is composed of the loading time at the in-woods landing, driving loaded to the mill, mill unloading time or mill turn time, and the return trip unloaded to the landing. Loading time at the landing is determined within the model based on the amount of wood inventoried at the landing when a truck arrives and the loading rate specified by the user. If a truck arrives and there is not enough wood inventoried on the landing to complete the truckload, then the rate of wood flow from the harvesting system and merchandising rate will impact the amount of time required to complete the truckload. Once a truck is fully loaded it begins its trip to deliver wood to the mill. When a truck leaves the landing the "stock" of trucks available to use decreases. The specified time for driving loaded to the mill includes the total time from when the truck is fully loaded and pulls away from the loader at the in-woods landing until it arrives at the receiving mill. Turn time at the mill consists of the total time from when the truck has to stop at the mill, until it is unloaded and can drive away from the mill to begin its return trip. The return trip is composed of the time required for the truck to drive from the mill, arrive at the landing and position itself for receiving a load of wood from the loader. If a truck in the model cannot complete its delivery, return to the landing and receive another load of wood before the end of the scheduled day for the harvesting crew then the truck will not haul another load of wood for that day.

The model user specifies the number of hours per day the harvesting crew and loader will operate, but once a truck is loaded it will continue its delivery trip to the mill regardless of whether or not the in-woods crew is still working. The model does not take into account any regulatory restrictions that may be imposed on the number of hours an individual truck driver may be allowed to operate. Therefore the assumption was made that if a truck arrived at the landing and was loaded before the end of the scheduled harvesting crew workday, the truck would be able to complete the delivery to the mill regardless of the number of hours the truck driver had previously operated that day. The assumption was made that once a load of wood has been delivered, the truck will return to the landing for another load. The fact that trucks automatically return to the landing leads to a situation where the truck ends up waiting "overnight" at the landing for the harvesting crew to start up the next morning. However, the number of hours that the truck spends at the landing is only calculated during the scheduled harvesting crew workday. Therefore this approximates an actual system where at the end of a workday the truck makes its last delivery to the mill and is available at the landing the next morning when the in-woods crew begins work.

When the model user specifies that multiple products are merchandised from the harvested wood, before a truck can be loaded, a decision must be made as to which product will be loaded on the truck. While in reality, the exact hours that receiving mills accept wood may influence the decision as to which product the contractor will load, the simplified LTSS model structure cannot accept inputs to schedule truck departures based on receiving hours at the mill. Therefore the assumption is made that the hours when mills receive wood is not a limiting factor. If there is enough of one product inventoried on the landing to fill the truck to its maximum payload, then the truck will be loaded from the largest product inventory on the landing. However if there is not enough of any individual product inventoried on the landing to complete the load, then the model must make a decision as to which product to load. The decision is based on whether or not the amount of a product inventoried on the landing, plus the amount of that product expected to be skidded onto the landing in the next half-hour will be enough to complete a full truckload. If the model does not force the loading decision for multiple products to wait until there is almost enough wood to complete a load, then a harvesting shutdown can occur. The shutdown occurs when a product is being loaded on a truck, but the landing reaches maximum capacity with other products while waiting for enough wood to complete a load of the product being loaded. Once the truck is fully loaded it travels to the specified mill for the product it is carrying. After the truck is unloaded at the mill, the payload the truck was carrying becomes mill inventory and the truck returns to the landing. The stand harvest is completed when the total tons of wood remaining in the stand equals zero. The total harvesting job is considered complete when the last remaining wood is trucked from the contractor's landing.

3.3 Estimating the Contractor's Harvesting and Trucking Costs

The purpose of including cost calculations in the LTSS model is to illustrate the magnitude of cost changes as trucking affects the contractor's total system productivity. Cost inputs and equations for calculating harvesting and trucking costs are of a simplistic nature so that a minimal amount of cost data is required in order to run a simulation and obtain a cost estimate. The cost calculations are not intended to provide a detailed analysis of costs incurred by the logging contractor.

The primary output of the LTSS model is the change in the contractor's total system production (loads or tons delivered per day) as a result of changes in the trucking system. Using basic cost structure information for an individual contractor, cost per delivered ton is calculated by the model based on total production and the amount of time required to harvest the stand.

<u>Harvesting Costs</u>

The basic cost components for a harvesting operation based on the machine rate approach are fixed costs, variable costs and labor costs (Greene and Lanford, 1999). The following calculations are used in the model to estimate the cost per ton of wood produced from a stand harvest.

<u>Total Harvesting Cost =</u>

(Fixed harvesting costs per day × days to harvest the stand)

\+

(Variable harvesting cost per productive hour × total scheduled hours × harvesting crew utilization)

\+

(Harvesting labor cost per hour × scheduled hours to complete the harvesting job)

where,

- Fixed harvesting costs per day = Annual fixed costs (which include equipment payments, depreciation, insurance and other overhead) ÷ days worked per year.

- Variable harvesting costs per productive hour = average cost of fuel, maintenance and repair, and other consumables per operating hour for equipment in the harvesting system as a whole.
- Harvesting crew utilization = actual hours worked ÷ total scheduled hours.

Trucking costs for the delivery of wood were based on an average cost per day to own and operate a truck. Calculating trucking costs based on a cost per day to own and operate a truck keeps trucking cost inputs simpler and requires fewer model inputs (Steve Carruth, pers. comm., Westvaco Corp. Rupert, WV). Using the cost per day to own and operate a truck assumes an average usage rate of variable costs such as fuel and tires, as well as the fixed cost of owning the truck, plus the labor cost for the driver's pay. The cost per day to own and operate a truck treats trucking cost as a fixed cost and the cost per delivered ton is directly related to the number of loads delivered per day. Therefore trucking costs in the model are calculated based on the following formula.

Trucking costs =

Cost per day to own and operate a truck × number of trucks × days to complete delivery of wood harvested from the stand.

Total cost per delivered ton from the stand harvest =

(trucking costs + harvesting costs) ÷ total tons delivered

Using a cost per day to calculate trucking costs would tend to underestimate actual costs when trucks are utilized more and spend more time driving on the road. Trucking costs would tend to be overestimated when trucks are less utilized and the percentage of idle time is higher. The primary purpose of including the cost calculations was to illustrate the general nature of cost impacts to the logging contractor. If the purpose of the cost calculations were to provide a more precise cost estimate for the trucking system, then a more detailed calculation for trucking costs would be appropriate. A more detailed calculation for trucking costs would include fixed costs for the truck, labor costs, and variable costs per mile driven.

3.4 Model Inputs & Outputs

The model interface allows the user to describe production rates for wood flow through the logging contractor's system by entering the desired parameters next to a variable's name in a manner similar to the way a spreadsheet would operate. Model inputs for quantities of wood are in tons and production rates are in tons per hour. Inputs for driving times and mill turn times are in minutes. Outputs are updated on the control panel as the simulation progresses and final output values are retained on the screen at the end of a simulation.

3.4.1 Production Inputs

Production inputs required for describing the flow of wood through the contractor's system in the LTSS model are summarized in Table 3.1. Most of the inputs are easily obtained by observing the contractor's operation (number of trucks, storage capacity on the landing, hours worked per day, etc.). Others may require more effort to obtain from an actual contractor's operation. The merchandising rate can be determined by observing the loader in operation and dividing the total number of tons merchandised by the total hours spent merchandising. If the merchandising rate is not known for a contractor's operation, but is not a limiting factor that affects production, the merchandising rate can be set to its maximum value of 500 tons per hour. Wood will quickly flow through the merchandising process and should not be a constraint to system production. The merchandising rate can also be set to its maximum value to approximate the operations of a contractor's system that does not merchandise wood at the landing. The loading rate in tons per hour can be determined for an actual contractor's job based on the total tons of processed wood loaded onto a truck(s) divided by hours spent loading the truck(s). The harvesting rate input is the average rate in tons per hour that the contractor's harvesting crew will produce wood over the course of a scheduled day unless storage at the landing is a constraint and the crew must stop production. The harvesting rate for a specific contractor's operation is determined by the total tons produced per day divided by the number of scheduled hours the contractor works per day. Additional hours per day when trucks can be loaded but the harvesting crew is idle is an input that allows the user to model situations where trucks may arrive and are loaded during lunch breaks or at the end of a day when the harvesting crew is not producing. Since the harvesting crew isn't producing, no additional wood flows onto the landing during this time but the truck can be loaded if there is enough of a particular product on the landing to complete the truckload.

Table 3.1 Production inputs required for LTSS model simulations.

Production parameter	Description
Stand size	Total tons of merchantable wood in the stand to be harvested.
Maximum product storage on landing	Tons of wood that can be stored at the contractor's landing before the harvesting crew will go idle because of storage limitations.
Trucks assigned to job	Number of trucks the contractor has available to use on this harvest operation.
Harvesting rate	Production rate in tons per scheduled hour that the harvesting crew is capable of producing when storage at the landing is not a constraint. The crew will produce at this rate for the entire scheduled day unless maximum storage is reached at the landing.
Merchandising rate	The rate in tons per hour that the loader can process wood to prepare it for loading on a truck.
Loading rate	The rate in tons per hour that the loader can load a truck from inventory of wood on landing.
Scheduled hours per day for harvesting crew	Number of hours per day the harvesting crew is scheduled to work.
Additional hours when trucks can be loaded but harvest crew is idle	Hours such as a lunch break or at the end of the day when trucks can be loaded if they are available on the landing. Wood can be merchandised and sorted during this time, but no more wood comes onto the landing from the harvesting crew.
Product percentages	Percent of merchantable tons of each product in the stand to be harvested.
Average truck payload	The average tons of payload each truck can haul.
Average drive time to mill	Average number of minutes required for a truck to go from the loader at the in-woods landing to the receiving mill.
Average mill turn time	Average number of minutes spent at the receiving mill from the time the truck has to stop at the mill entrance, until the truck can pull away from the mill.
Average drive time unloaded	Average number of minutes required for the truck to drive from the mill to the loader at the landing.

3.4.2 Cost Inputs

Cost information is not required to perform a simulation. However, if the model user wishes to estimate impacts to the logging contractor in terms of costs, then cost input parameters (Table 3.2) are required. The model control panel contains a range of possible cost structures for three typical contractor's operations from the Appalachian region (Appendix B) (Steve Carruth, pers. comm.) to allow the model user easy access to a range of possible input values to predict costs.

Table 3.2 Cost input parameters required to estimate harvesting and trucking costs for an LTSS model simulation.

Cost Parameter	Description
Annual fixed harvesting cost	Total fixed costs incurred per year. Includes equipment payments, insurance premiums, licenses, and other costs that do not change based on production.
Hourly harvesting labor cost	Combined hourly cost to the logging contractor for all in-woods harvesting employees.
Variable cost per productive hour	Average variable costs per productive hour for the harvesting crew as a whole. Includes costs such as fuel, tires, tracks, maintenance and repair that will only be incurred when the harvesting crew is operating.
Days worked per year	Average number of days per year the harvesting crew will operate.
Cost per day to own and operate a truck	Estimate of an average total cost per day of owning and operating each truck in the fleet; includes driver's pay, fixed costs and variable costs.

3.4.3 Model Outputs

Based on the user specified production rates for the contractor, as well as product percentages and mill destinations, the model calculates and reports the number of loads or tons of wood produced per day. Outputs related to time elements are calculated using "flows" and "converters" within the model that track the time spent in various processes to illustrate where system delays are occurring. Model outputs are reported on the control panel of the model interface.

Table 3.3 Description of outputs from an LTSS model simulation.

Model Output	Description
Average loads per day of each product	Total loads of each product delivered divided by days to complete delivery of wood.
Total loads per day	The sum of loads per day of each individual product.
Tons delivered per day	Total tons delivered to mill inventory divided by days to complete the harvest.
Total loads delivered	Total truckloads of wood delivered from the stand harvest.
Days to complete harvest	The number of scheduled harvesting crew workdays required for harvesting and transporting all wood from the landing.
Truck hours per day	Average hours per truck per day spent driving to and from mill(s), at the mill(s), and at the landing during the scheduled day for the harvesting crew.
Truck hours at mill(s)	Total hours trucks spend at receiving mill(s).
Percent of truck time at mill(s)	Percentage of truck hours per day spent at receiving mill(s).
Truck hours on the road	Total truck hours driving to and from receiving mill(s).
Percent of truck time on road	Percentage of hours available per truck day actually spent driving to and from the receiving mill(s).
Truck hours at the landing	Total truck hours at the in woods landing. Includes time actually being loaded, and idle time waiting to be loaded.
Percent of truck time at the landing	Percentage of hours available per truck day at the contractor's in-woods landing.
Idle truck hours at the landing	Total hours trucks spend idle at the landing. Idle hours include all truck time at the landing except for the time when the truck is actually being loaded.
Landing time per truckload	Average number of minutes trucks spend at the landing for each load of wood delivered, includes idle and loading time.
Trucking utilization percentage	Percentage of truck hours per truck day when trucks are being loaded, driving to or from the mill, or at the mill.
Harvesting cost per ton	Total harvesting costs for the stand harvest divided by the total tons delivered.
Trucking cost per ton	Total trucking cost divided by the total tons delivered.
Total cost per ton	Sum of trucking and harvesting costs per ton.
Harvesting crew utilization percentage	(Actual hours worked by the harvesting crew $\div$ total scheduled hours) $\times$ 100
Lost production per day	Average tons of harvesting production lost per day when the harvesting crew was waiting on storage space at the landing (idle hours per day $\times$ harvesting rate per hour).
Estimated number of additional trucks needed to maintain maximum production	An estimate of the number of trucks that would need to be added to the trucking system (if round trip truck times are the production constraint) so that trucking delivery capacity will not limit production. Estimated based on average tons delivered per truck per day $\div$lost production per day.

3.5 Randomization Feature of the Model

Because of variation in driving times along the same route to a mill, and mill turn times at the same mill, average times may not necessarily be the best representation of the times expected for truck deliveries over the course of a stand harvest. In order to illustrate potential impacts due to variations in delivery times the model was constructed with the capability of randomly selecting times from within a statistical distribution. When the model's randomization feature is activated, instead of using the average time specified by the user for drive times and mill turn times; the model randomly selects times from within a distribution of times that has approximately the same average as the user specified time. Each time a simulation is performed with the randomization feature activated, outputs can be different as different times are randomly selected for each truckload delivered.

3.5.1 Data for Determining a Randomization Distribution

In order to determine which statistical distribution to use for randomly selecting times, data was obtained for mill turn times and for truck driving times to and from the mill. Mill turn time data was previously collected from a study where truck drivers were asked to fill out a time sheet for each load of wood delivered to three different receiving mills or concentration yards in the Appalachian region (Steve Carruth, pers. comm.). The distribution of turn times from mill number one is illustrated in Figure 3.3. Histograms of turn times from mills number two and three are included in Appendix C.

Truck drive times were collected using a Global Positioning System (GPS) receiver and data recorder mounted on a log truck. The GPS receiver uses satellites to track the location and speed of the truck, and every two minutes the data recorder automatically records the location and speed of the truck. The data recorder stores the information on a removable card similar to a computer floppy disk. The data can then be downloaded to a desktop computer. Driving times were measured from the time the truck left the in-woods landing until the time the truck arrived at the mill. When recording individual trip times the assumption was made that the drive times of interest were for direct trips to the mill and from the mill. As a result, stops in excess of 10 minutes such as lunch breaks, trips home, and overnight stops were subtracted from the trip time. The distributions for truck drive times loaded and unloaded are included in Appendices D and E.

3.5.2 Using the Data to Allow Random Time Selection in the Model

A visual inspection of histograms of the mill turn time data indicated that the data had characteristics of a Weibull distribution (Richard Oderwald, pers. comm.,Virginia Tech Forestry Department). The Weibull distribution has been used as a distribution for a variety of applications (Kotz and Johnson, 1989). The data for mill turn times and driving times were fitted to a Weibull distribution using the SAS version 8 statistical package (SAS Institute Inc., 1999). The SAS output provides a histogram of the mill turn time data along with a Weibull curve fitted to the data (Figure 3.3). The SAS output also includes fitted parameters of the distribution and the results of goodness of fit tests (Figure 3.4) that describe how well the observed distribution fits the expected distribution (Howell, 1997).

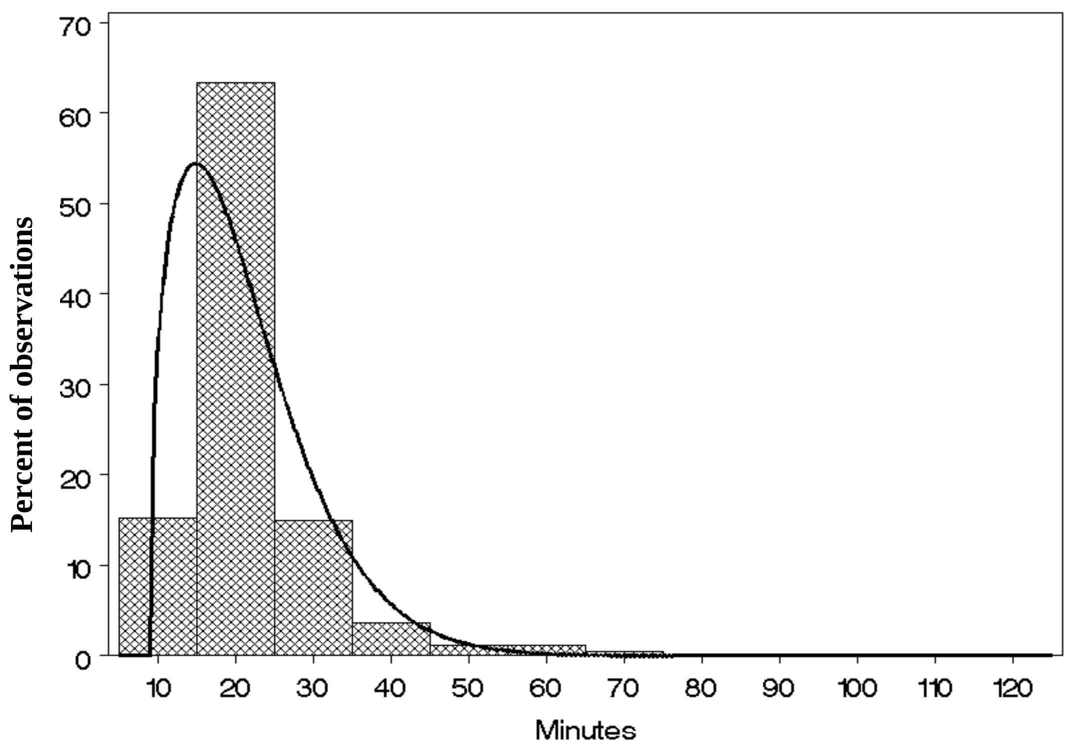

Figure 3.3 Weibull curve fitted to turn time data for mill number one.

Parameters for Weibull Distribution

Parameter	Symbol	Estimate
Threshold	Theta	8.897947
Scale	Sigma	13.5643
Shape	C	1.438354
Mean		21.21087

Goodness-of-Fit Tests for Weibull Distribution

Test	---Statistic----		-----p Value----	
Cramer-von Mises	W-Sq	2.0667230	Pr > W-Sq	<0.010
Anderson-Darling	A-Sq	12.1429899	Pr > A-Sq	<0.010

Figure 3.4 SAS output of fitted parameters and goodness of fit test for distributions of mill turn time data for mill number one.

The model generates random numbers from within a Weibull distribution based on the following formula (HPS, Inc. 2000b).

Weibull distribution = b * (-LOGN(RANDOM(0,1)))^(1/c) + a

where, a >= the location (threshold) parameter

b >0 the scale parameter

c >0 the shape parameter

While data was available for three different mills, the Weibull distribution for mill number one (Figure 3.3) was chosen as the default distribution for turn time randomization within the model because of the greater number of turn time observations. The default Weibull distributions for drive time loaded and unloaded are included in Appendix D. The selected Weibull distributions are provided as the default distributions, however the LTSS model contains input tables where parameters from other fitted Weibull distributions could be entered if the user desired.

When randomly selecting times in the model, the assumption is made that the distribution parameters are for the shape of a typical distribution of mill turn times and drive times. For example the user may input different average turn times for each receiving mill, but each will use the same distribution shape parameters. The distribution will be shifted to the left or the right to approximate a distribution with an average value approximately the same as the average value specified by the user.

3.6 Time Interval Used for Simulation Calculations

In the Stella® modeling environment, "flows" are the manner in which the product (wood) moves from one model process to another. In the LTSS model, the unit of measure for wood is tons, and the unit of measure for time is hours. Therefore "flows" are defined in terms of tons per hour. ΔT is the interval of time between the model's internal calculations (HPS Inc. 2000b). In the LTSS model, ΔT was specified as a fraction where the denominator of the fraction represents the number of times per hour calculations are performed. When ΔT is specified as 1/1, calculations are performed once per hour in the simulation. For example, assume there is a "flow" where its equation designates the flow as 100 tons per hour. If ΔT is 1/1, the computer calculates the flow equation one time each hour, and with each calculation, 100 tons of wood can move through that flow. If ΔT is decreased to 1/20, calculations are performed 20 times per hour, and with each calculation five tons of wood can move through the flow. As ΔT decreases, the computer time required for performing the simulation increases. In addition, there is a limit to the number of calculations that the software will perform for any single simulation. Therefore as ΔT decreases the total number of hours that can be simulated decreases because the limit for the number of calculations is reached sooner.

Changing ΔT can change model outputs. The exact change will depend on the system being simulated. To illustrate potential changes in output as ΔT changes, an example contractor's production inputs (Table 3.4) were used to perform simulations where ΔT

decreased with each simulation. Outputs for the hours that trucks spent at the mill and at the landing varied as ΔT changed (Figure 3.5). The variation is most pronounced when ΔT is large and becomes less pronounced when ΔT is smaller. The model output of loads produced per day for the example scenario also varied as the ΔT decreased (Figure 3.6).

Table 3.4 Example production inputs used to illustrate impacts of changing DT.

Production input parameter	**Value used for example scenario**
Stand size in tons	4000 tons
Maximum product storage at landing	100 tons
Harvesting rate	20 tons per hour
Merchandising rate	50 tons per hour
Loading rate	75 tons per hour
Scheduled hours per day	9
Number of trucks available	2
Additional hours per day trucks can be loaded but harvesting crew is idle	0
Average truck payload	25 tons
Drive time to and from mill	60 minutes
Average mill turn time	21 minutes

The total amount of wood that flows through each process remains the same regardless of the ΔT value used. However outputs related to time can change as a result of the model's internal calculations of the time that the product spends in each step along the way. The default ΔT setting in the LTSS model is 1/20 of an hour, or 3 minutes. The model user should be aware that changing the ΔT could change model outputs. Model outputs for the individual time components in particular are more sensitive to the effects of ΔT.
The ΔT used for model calculations can be changed in the model's Time Specs dialog on the Run menu if the user wishes.

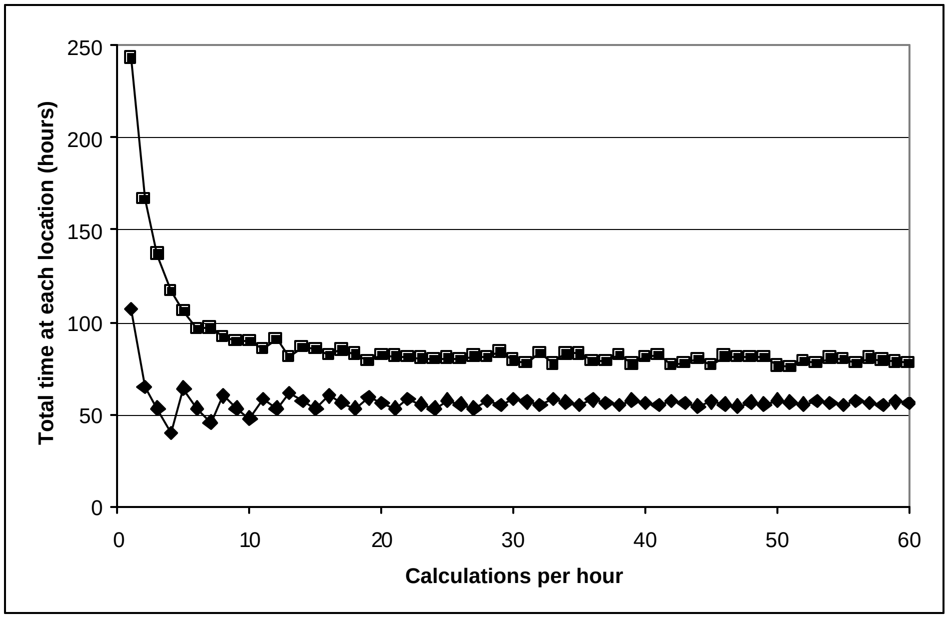

Figure 3.5 Change in model outputs of truck time at the landing and mill as DT decreases and the calculations performed per hour in the model increase.

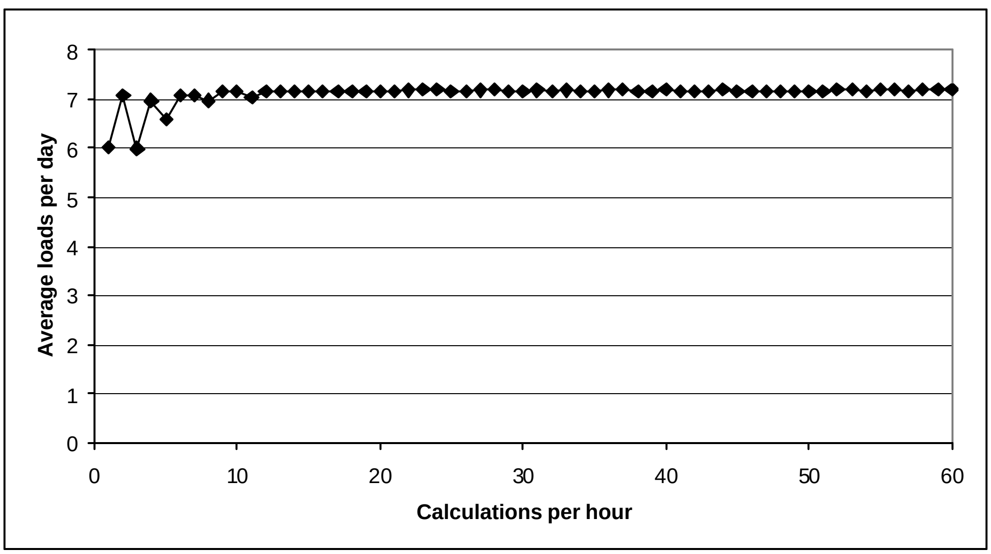

Figure 3.6 Change in output of average loads produced per day as DT decreases and the calculations performed per hour in the model increase.

CHAPTER 4 TESTING THE MODEL

The LTSS model predicts average production of truckloads of wood from a logging contractor's system based upon production inputs for wood flow throughout the modeled system. In order to verify that the model adequately represents wood flow from logging contractor's systems, production rates and system inputs from actual contractors were used as input data for a stand harvest with the LTSS model. The observed production rates were compared to the predicted production rates from the stand harvest with the LTSS model. Production rates used for model inputs were obtained from a series of single day "work sample" observations of independent logging contractors in the Appalachian region (Appendix F). The "work sample" data set included 19 usable work sample observations. Four sample days within the data set were not used because truck delivery times were unknown. The work sample data contained the actual number of truckloads hauled from the contractor's operation on the observed day and the observed truckloads produced for the day based on the estimated tons produced ÷ average truck payloads. The contractor's observed production rates in tons per hour were used as model input production rates for a stand harvest with the LTSS model.

In the work sample observation, when a truck left the landing, the departure time and type of product trucked were recorded. Model inputs for product percentages in the stand were assumed to be the same as the percentage of products represented in the truckloads delivered that day. If the truck returned to the landing during the day of observation, the total round trip delivery time was recorded. When multiple deliveries of the same product were made, the average total round trip delivery time for each product was used to determine the delivery time inputs. In some cases, no round trip delivery times were available for delivery to a particular mill because the truck did not return to the landing that day, however, it was possible to estimate the trip time using the distance to the mill and average truck speed.

Work sample observations were made from the contractors in-woods operation, as a result, only total truck delivery times could be observed. Data for individual segments of the round trip truck delivery time were not available. The total delivery time consisted of driving to and from the mill as well as mill turn time. An average mill turn time of 21 minutes was assumed based on the average turn time for mill number one (Figure 3.4), and an assumption was made that drive times to and from the mill were equal. The assumed mill turn time of 21 minutes was subtracted from the total recorded round trip delivery time and the remaining trip time was divided equally between drive time to and from the mill.

An assumption was made that the contractors in the work sample observations were able to produce all day on the work sample day without storage constraints at the landing. Therefore the work sample observation of average productivity per scheduled hour for the skidding function was used as the model input for harvesting production rate. The merchandising rate and loading rate inputs were the rate per productive hour.

The underlying model assumption is that wood is skidded onto the landing from the harvesting crew at a known constant rate of production unless the trucking system is a limitation and production stops because of storage limitations at landing. With the assumption of a constant production rate throughout the stand harvest, model outputs of average loads produced per day would be expected to be the same as the observed number of loads produced (tons produced ÷ average truck payload) on the observation day unless trucking limited production. If the model predicts that trucking is a limiting factor based on trucking inputs for the observed day, then the output of average loads per day would be expected to be less than the observed loads produced per day because the contractor could not continue to produce in excess of their trucking capacity.

The results of the model tests show the actual loads produced on the observed day (tons produced ÷ average truck payload), actual loads hauled on the observed day, and the model output of predicted average loads produced per day during over the course of the stand harvest. In five of the nineteen work sample days (Figure 4.1) the actual loads hauled by the contractor were the same as the actual number of loads that they produced.

As expected, the average total loads per day predicted by the model were very similar to the actual total loads produced and hauled on the observed work-sample days.

On three of the work sample observation days, contractors hauled more loads than they actually produced (Figure 4.2). These contractors obviously had a higher production rate on previous days and additional wood was inventoried on the landing at the beginning of the day. During the stand harvest the model assumes the same constant harvesting production rate for the contractor as the input value for the observed day. Even though the contractor may have had the trucking capacity to deliver more wood, production from the harvesting crew was the limiting factor. Therefore average loads per day predicted by the model were very similar to the observed production from the harvesting crew on the sample day.

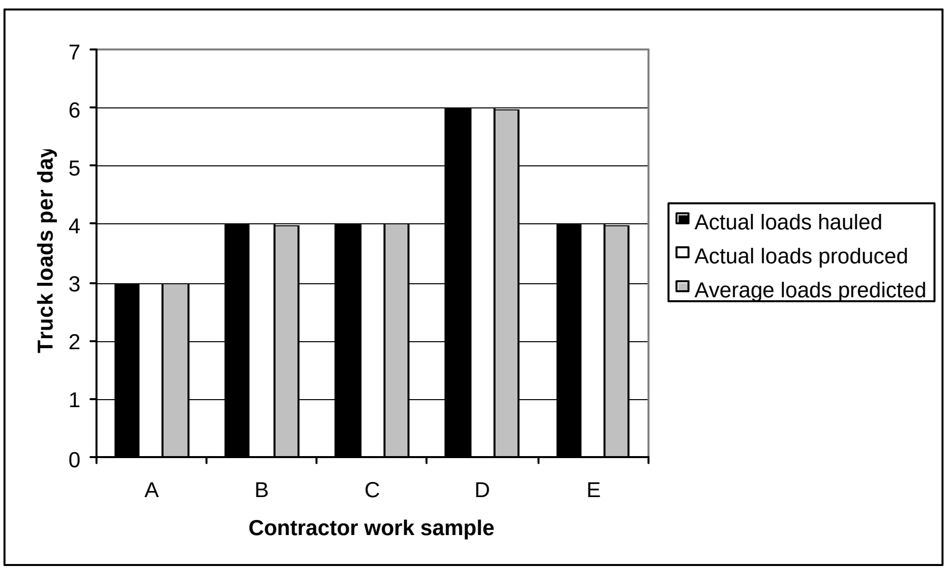

Figure 4.1 Contractor work samples where loads produced and loads hauled equaled loads predicted.

Seven of the contractor's work sample observation days (Figure 4.3) had actual loads produced that exceeded loads actually hauled for the sample day. However, based on the trucking production inputs the model did not show trucking to be a constraint. As a result, when trucking is not a constraint, the average number of loads per day predicted for the stand harvest was very similar to the actual loads produced for the observed day.

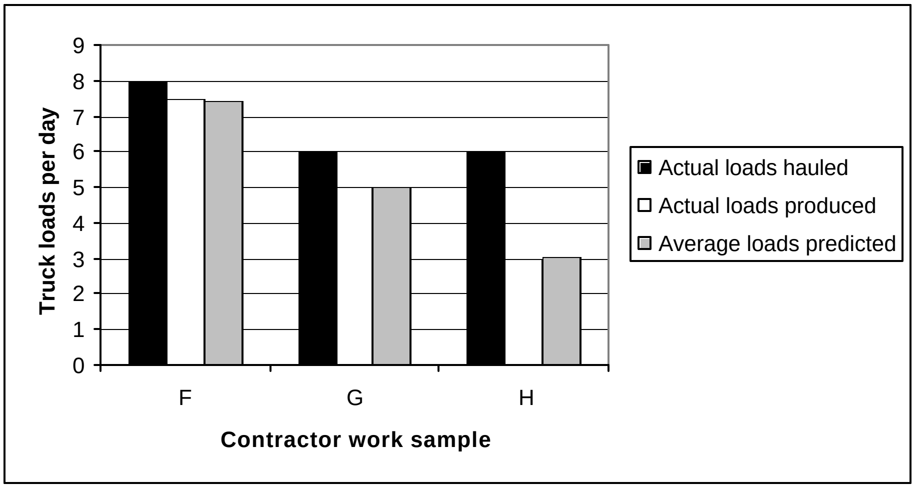

Figure 4.2 Contractor work samples where loads hauled exceeded loads produced and loads predicted.

Even though the number of loads they actually hauled was less than the number of loads produced, contractors I through M showed differences in production of one load or less. The differences in production for contractors I and M may be explained by the effect of averaging when the stand harvest was performed. For example with contractor I, average loads predicted was approximately 7.6 loads per day and on the observed day only seven loads were hauled. To get an average of 7.6 for the stand harvest, some days would have had 7 loads of production like the observed day and some days may have had production higher or lower than 7 loads per day. Another possible explanation for differences in production for the contractors represented in Figure 4.3 could be that the timing of wood flows onto the contractor's landing impacted truck departures differently in reality than in the simulation. In addition, actual loads hauled could be different from actual loads produced and average loads predicted as a result of additional products that were actually harvested but not recorded because they were not trucked on the observation day. These additional products could have been inventoried on the landing at the end of the day and implied that there was enough wood present on the landing to complete a whole truckload, while in reality there was not an entire truckload of any single product available to truck. Contractors N and O however showed greater differences between actual loads hauled and the loads produced and loads predicted. These contractors likely had a system limitation, other than truck turn times, which prevented them from trucking as many loads as possible based on observed production rates and round trip truck times.

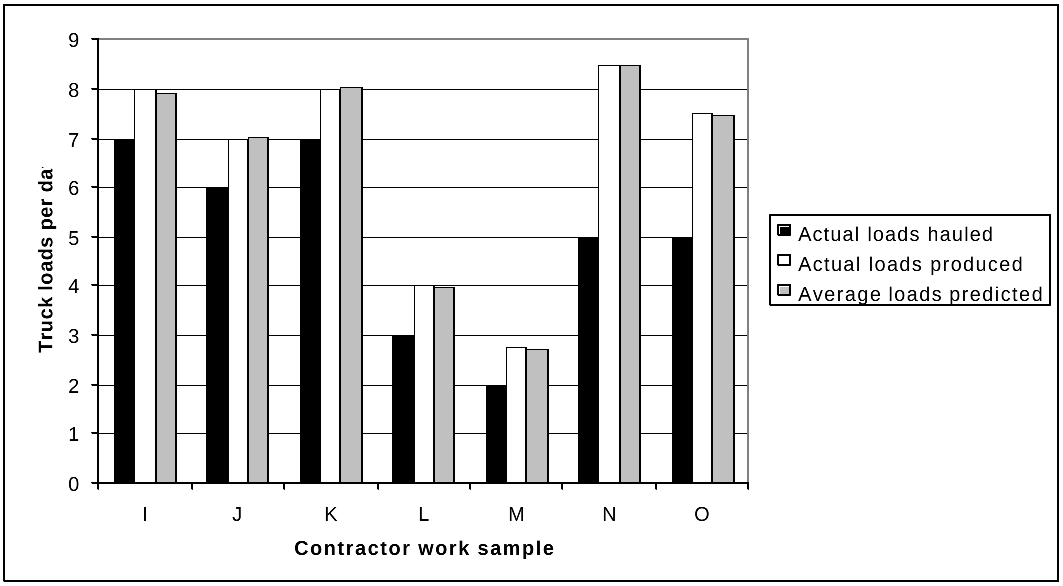

Figure 4.3 Contractor work samples where loads produced and loads predicted exceeded loads hauled.

Four contractors in the work samples had actual loads delivered that were less than the actual loads produced, and when the simulation was performed, the model indicated that the trucking system was out of balance with in-woods production (Figure 4.4). Maximum inventory was eventually reached at the contractor's landing and the harvesting crew had to halt production for a period of time. Due to the trucking constraint, the model output of average loads produced per day from the stand harvest was less than the observed loads produced.

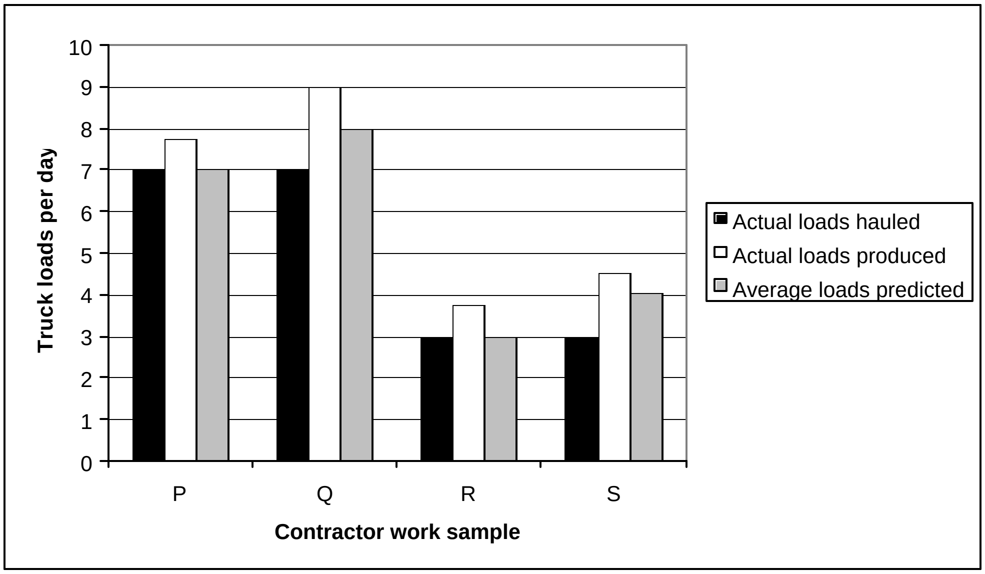

Figure 4.4 Contractor work samples where loads predicted were less than loads produced and the model illustrated that trucking limited production.

Testing the model using previously collected single day work-sample data illustrated the model's ability to represent wood flow from actual contractor's systems. Based on production inputs and the model's wood flow assumptions, model outputs of predicted average loads per day were basically the same as the contractor's actual number of loads produced on the observed day unless trucking was a limiting factor. When the model indicated trucking was a limiting factor, average loads per day predicted from the stand harvest were less than the actual loads produced because trucking would ultimately limit production.

CHAPTER 5 EXAMPLE MODEL SIMULATIONS

Once the model has been constructed and tested, example simulations can be performed to illustrate impacts to a logging contractor as the contractor's trucking system limits total productivity. The possible combinations of harvesting production rates, harvesting systems and cost structures for logging contractors are virtually limitless. A hypothetical contractor's system was used as an example (Table 5.1) to illustrate the nature of the impacts caused by delays at different points in the truck delivery system. Exact output values for any particular logging contractor's operation will depend on the specific inputs for the operation. However the example scenarios illustrate the nature of the impacts associated with imbalances between the trucking and harvesting systems.

Table 5.1 Contractor's production and cost inputs used for example simulations.

Production input parameter	Value used for example scenario
Stand size in tons	4000 tons
Maximum product storage at landing	100 tons
Harvesting rate	20 tons per hour
Loading rate	75 tons per hour
Merchandising rate	50 tons per hour
Scheduled hours per day	9
Additional hours per day trucks can be loaded but harvesting crew is idle	0
Average truck payload	25 tons
Average mill turn time	21 minutes
Cost input	**Value used for example scenario**
Annual fixed harvesting cost	$165,000
Labor cost per hour for harvesting crew	$160
Variable cost per productive hour	$70
Days worked per year	230
Cost per day to own and operate a truck	$525

A stand size of 4000 tons was chosen to allow a sufficient number of days of harvesting production to obtain an average production value without creating an excessively long simulation. Merchandising rates, loading rates, and harvesting rates for the example system were approximated based on the average production rates for the independent contractor's work samples used for testing the model (Appendix F). An assumption was made that trucks would only be loaded when the harvesting crew was working, so the additional hours after the scheduled harvest day that trucks could be loaded was set to 0. Maximum product storage at the landing of 100 tons was based on landing storage restrictions that may occur in the Appalachian region and the average truck payload was assumed to be 25 tons (Robert Shaffer, pers. comm., VA Tech Forestry Department). Cost inputs were obtained from a range of typical contractor's costs (Appendix B) and an assumption was made that the harvesting crew would be able to operate 230 days per year. The cost inputs used were from the high end of the cost range and may overestimate costs for some producers. However the purpose of including costs in the example simulations was to illustrate the magnitude of cost increases. Determining the specific value of cost increases was not the objective of the example simulations.

5.1 Impacts of imbalance between trucking and harvesting systems

An incremental analysis of driving times to and from the mill was performed to illustrate the overall impacts to the contractor's system from imbalances between trucking and harvesting systems. Production inputs for the example contractor's system (Table 5.1) were used for a stand harvest with one product type in the stand. An assumption was made that the drive time returning to the landing would be the same as the drive time to the mill. The contractor's system was first set up with only one truck available and simulations were performed using a range of drive times from 5 minutes to 240 minutes in 5-minute increments. To illustrate the impacts from adding additional trucks to the contractors trucking fleet, the number of trucks available was increased to two, and the incremental analysis was repeated. The incremental analysis was then repeated for fleet sizes of up to five trucks.

Total round trip truck delivery time determines the potential number of loads per day that a log truck can deliver. When the contractor's trucking system is capable of delivering more wood than is produced by the harvesting crew, then the production limitation for the contractor's system as a whole will be production from the harvesting crew. When truck delivery times increase to the point that the trucking system is no longer capable of delivering as much wood as is produced by the harvesting system then production from the contractor's system as a whole is limited to the delivery capacity of the trucking system.

Model outputs from the incremental analyses include average loads produced per day (Figure 5.1). No data is available for the system with one truck at a drive time of 240 minutes because the length of the simulation was too long for the entire stand to be harvested. The limitation from in-woods production is illustrated by the situations where, regardless of the number of trucks the contractor has, average production cannot exceed 7.2 loads per day. Each scheduled day, 180 tons of wood is produced from the harvesting system (20 tons/hour × 9 scheduled hours per day). When there is excess trucking capacity, on four out of five days, seven loads are hauled (7 loads per day × 25 tons per load = 175 tons per day). At the end of each day an extra 5 tons of wood remains that was harvested but not trucked away. Every fifth day, 8 loads can be hauled. Therefore when trucking is not the limiting factor, the number of loads delivered per day for this example contractor is approximately 7.2.

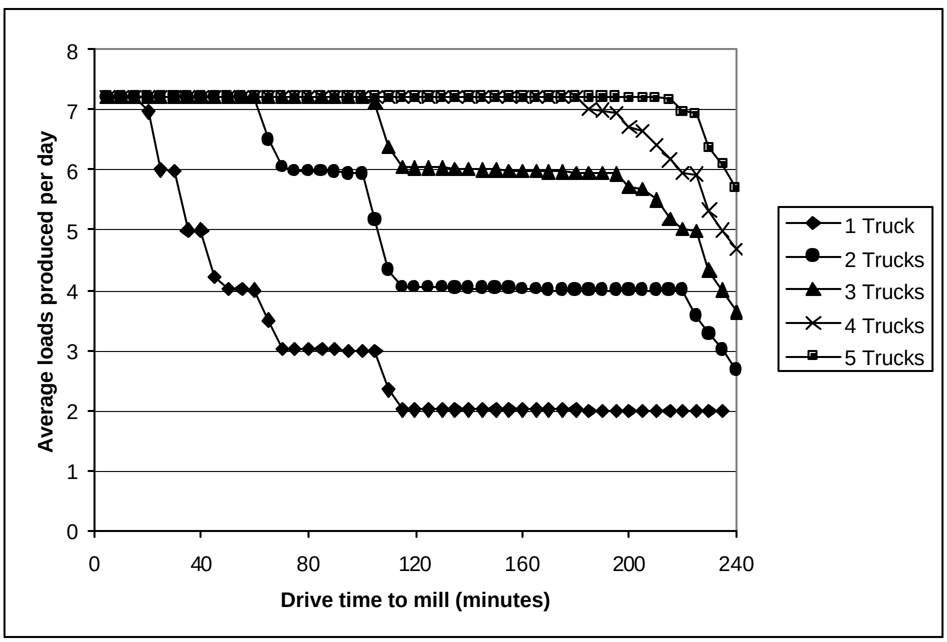

Figure 5.1 Average loads produced per day across different trucking scenarios as drive times to the mill increase.

The incremental analysis of drive times to the mill illustrates that the number of loads per day the contractor's system can deliver decreases in a stair step-like fashion. There are certain time segments over which the drive time to the mill can increase, but will not reduce the number of trips per day that the contractor's trucking system can deliver. In these time segments, slight increases or decreases in drive times result in the final load for the day leaving the landing earlier or later in the day, but the same whole number of loads are produced per day.

As drive times to the mill are incrementally increased, certain points are reached where trucking capacity is stressed and even a minor increase in the total trip time causes the average number of loads delivered per day to decrease. With drive times to and from the mill of 15 minutes or less, any of the trucking systems are capable of delivering all wood produced each day from the harvesting crew. As drive times to the mill increase, the number of loads per day each truck is capable of delivering becomes the limiting factor. In the example scenario, the trucks are all delivering to the same receiving mill. Therefore, most of the time each truck in the fleet is capable of delivering the same number of loads per day and the average total production from the trucking system is approximately a whole number value. At the critical points where increasing drive time by only a few minutes decreases the number of loads produced per day, the average number of loads per day may not be a whole number value anymore. At these critical points, the first truck(s) to get loaded in the day are able to make their delivery, return to the landing and get another load of wood, but the other trucks are not.

The data points representing the average number of loads produced per day show minor decreases between the major stair step-like decreases. Two factors are responsible for the minor decreases. The data points appear to "drift" slightly lower as a result of the way the average loads per day are calculated. Average loads per day = total loads produced ÷ days to complete the harvest. Days are calculated as portions of a whole day, and as drive time to the mill increases the trucking system is still capable of delivering the same whole number of loads each day but the final load may leave the landing later on the last day. When the harvest is completed later in the day, the denominator of days to complete the harvest is slightly larger, causing the output value of average loads per day to decrease slightly. Some of the minor decreases result where increased drive time to the mill reaches a point where on the first day of the harvest one less load of wood is delivered than on the rest of the harvest days. Consequently on the last day of the harvest the last load of wood also leaves the landing later in the day. As a result, the average loads produced per day shows a minor decrease at the point where the first day's production is decreased.

When the trucking system is not capable of delivering as many loads per day as are produced by the harvesting system, trucking capacity becomes the limiting factor. When trucking limits production, the storage space on the landing fills up and the harvesting crew must stop production and wait for wood to be trucked away before more storage space is available at the landing. As a result harvesting crew utilization decreases (Figure 5.2). Note that a decrease in average loads delivered per day (Figure 5.1) corresponds with a reduction in harvesting crew utilization (Figure 5.2) as production from the contractor's trucking system limits total system production.

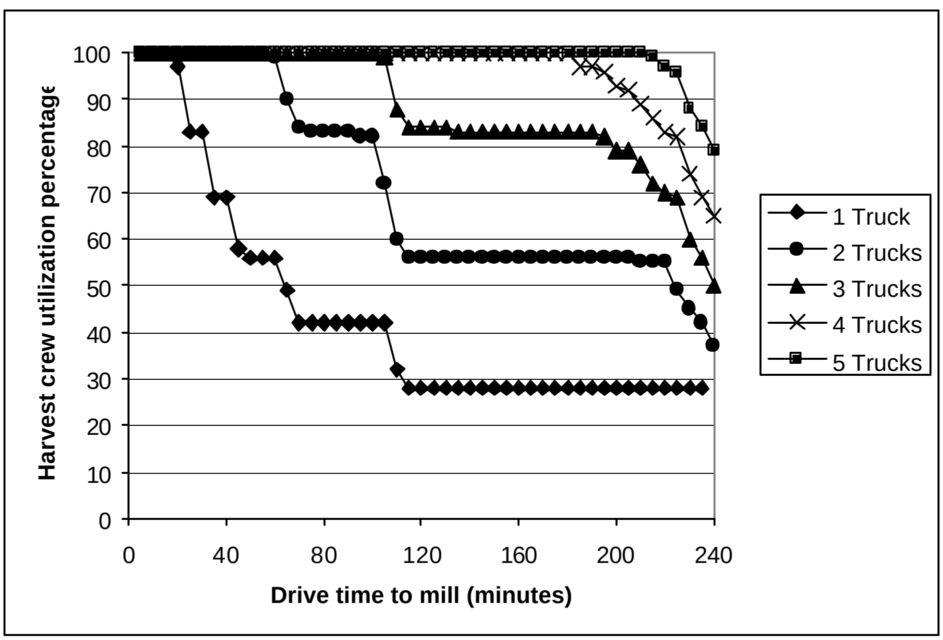

Figure 5.2 Harvesting crew utilization percentage across different trucking scenarios as drive time to the mill increases.

Harvesting crew utilization declines in a stair step-like fashion, as found with loads produced per day. Minor reductions in utilization rates between major stair step-like decreases are also apparent as found with average loads produced per day.

The model output for truck hours per day is calculated based on the average number of hours per truck per day that trucks spend on the road, at the receiving mill(s) and at the landing. The model also has outputs that track the average percentage of time each truck spends in these time segments. The percentage of truck hours per day spent in each segment of the total trip time changes as the drive time to the mill increases and trucking limits production. For the example contractor with two trucks, with shorter drive times, trucks spend more time idle at the landing waiting for enough wood to complete a load (Figure 5.3). As drive time to the mill increases the average percentage of truck time spent at the landing decreases. More time is spent actually driving on the road and more days are required to complete the stand harvest. Mill turn time is not increased in the incremental analysis. Therefore the total number of hours spent at the mill remains the same, but as the harvest takes longer to complete and the total truck operating hours increase, the percentage of time spent at the mill decreases.

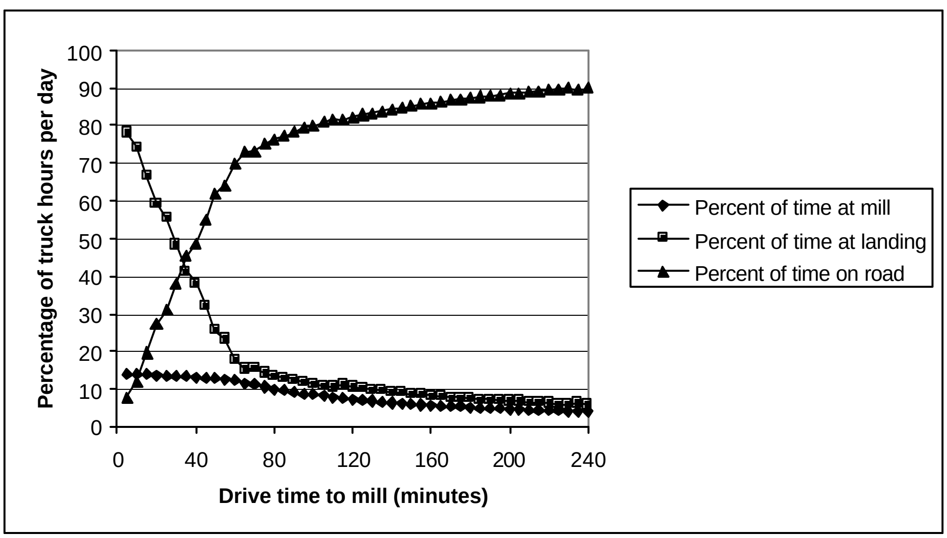

Figure 5.3 Percentage of truck hours per day spent at the landing, at the mill, and on the road as drive times to the mill increase.

The incremental analyses also indicate that as drive time to the mill increases to the point that the trucking system limits production, harvesting costs per ton increase (Figure 5.4). When the trucking system limits harvesting production, the harvesting crew goes idle but the model assumes they will stays at the job site for the entire scheduled day. Therefore labor costs are incurred for the whole day but in-woods production must stop until more wood is trucked away and more storage space is available at the landing. When the harvesting crew is idle, variable costs per day decrease, but more total days are required to harvest the stand (Figure 5.5), therefore the fixed cost and labor cost associated with each ton of wood produced increases.

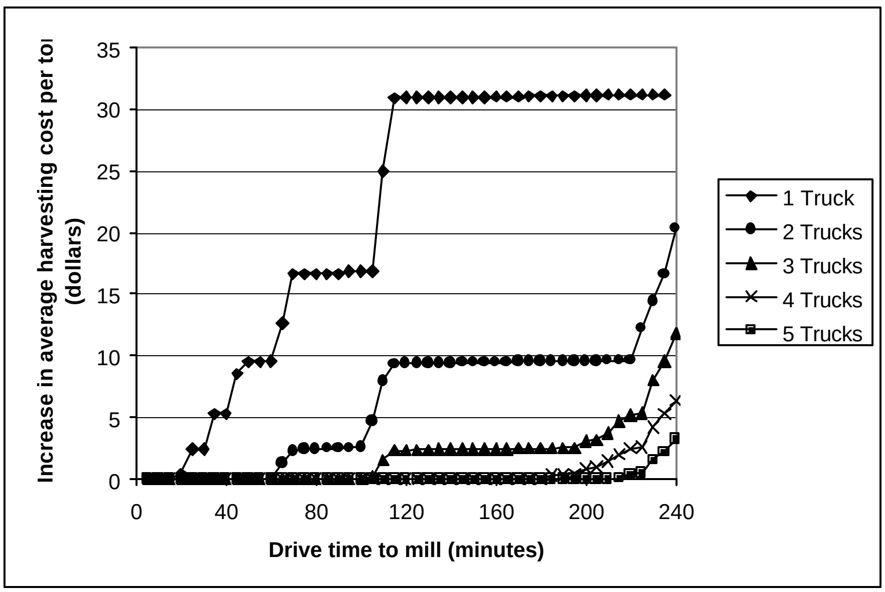

Figure 5.4 Increase in average harvesting cost per ton across different trucking scenarios as drive time to the mill increases.

For the example contractor's system, when drive time to the mill is 15 minutes or less, one truck is capable of delivering all wood produced per day by the harvesting crew, therefore production of the harvesting system is the limiting factor. When harvesting production is the limiting factor, adding additional trucks to the trucking system increases trucking cost per ton because the extra trucks do not result in increased production (Figure 5.6). Between approximately 120 and 200 minutes drive time, the cost increase lines overlap for trucking systems of one to three trucks, illustrating the fact that the trucking cost per ton is basically the same for this time segment. Referring back to Figure 5.1, under this segment of drive times, each truck in the fleet is delivering 2 loads of wood per day.

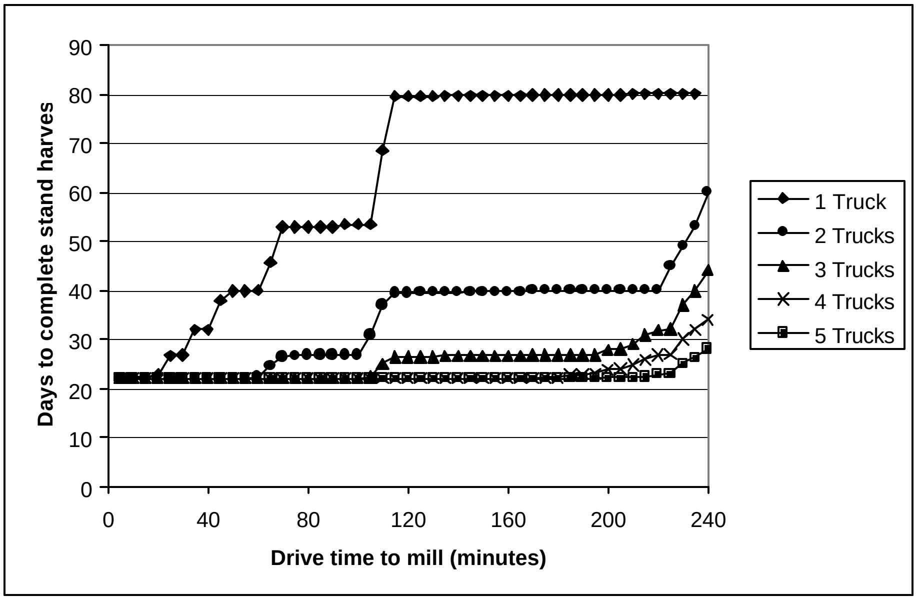

Figure 5.5 Days to complete stand harvest across different trucking scenarios as drive time to the mill increases and trucking limits production.

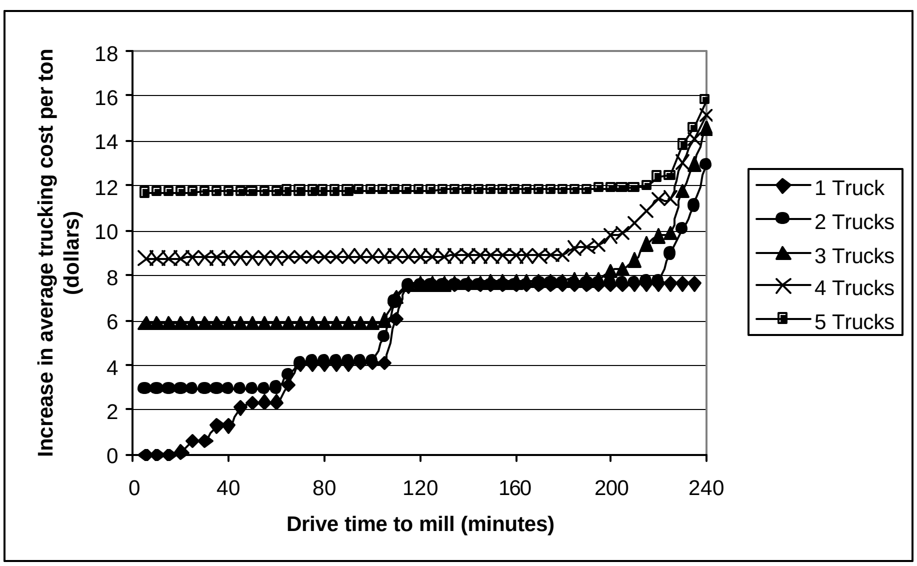

Figure 5.6 Increase in average trucking costs per ton across different trucking scenarios as drive times to the mill increase.

With the cost assumptions made in the model, trucking costs per delivered ton do not change unless the number of loads delivered per day changes. Since the cost per day to own and operate a truck is the same for each truck in the fleet, trucking costs on a per ton basis are the same for different fleet sizes when each truck in the fleet delivers the same number of loads per day.

While trucking costs per ton (Figure 5.6) may be the same for trucking systems with one to three trucks, and a range of drive times between 120 and 200 minutes, total costs per delivered ton are different (Figure 5.7). Total cost per delivered ton increases because of increased harvesting cost per ton as trucking limits production. As drive time to the mill increases, and trucking capacity becomes a limiting factor for trucking systems with fewer trucks, the cost of adding additional trucks is not as great as the cost associated with lost harvesting production.

Similar results were shown by Dremann (1986) using the TREESIM program based on the Auburn Harvesting Analyzer, with much more detailed cost inputs, as well as stand and harvesting system input requirements. The TREESIM program was used with an example contractor's system to illustrate that when trucking was limiting system production, total cost per unit of delivered wood decreased when additional trucks were added. The analysis also revealed that adding an additional truck increased total costs when it was not needed, but only a minor amount compared to the cost of not having enough trucks when trucking capacity was the limiting factor (Dremman, 1986).

The ideal truck fleet for a contractor is the number of trucks that allows the contractor to produce at the lowest total cost. However, the ideal size trucking fleet changes as drive time to the mill increases. The zone of least cost for the contractor represents the range where increased production from adding additional trucks to the trucking system more than offsets the cost of adding the additional truck. For example, with the contractor represented in Figure 5.7, when drive times are between 5 minutes and approximately 25 minutes, operating one truck enables the producer to produce at least cost. With drive times to the mill between approximately 25 minutes and 65 minutes, operating 2 trucks results in the lowest total cost per delivered ton.

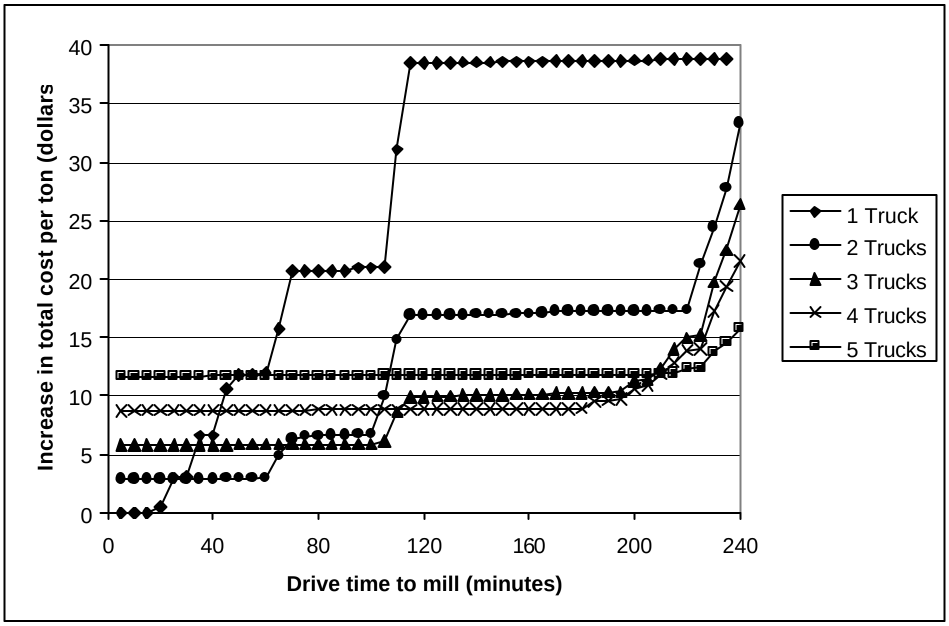

Figure 5.7 Increase in total cost per delivered ton across different trucking scenarios as drive time to the mill increases.

5.2 Impacts of Increasing Mill Turn Time

The time that trucks spend at the receiving mill is a part of the total trip time where delays can often occur. With the assumptions made in the model, the fact that a truck and driver has to spend an increased amount of time at the receiving mill does not necessarily mean the contractor's costs will increase. However the contractor's costs are impacted substantially when the increased time spent at the receiving mill decreases the average loads per day that the contractor's trucking system is capable of delivering and causes the trucking system to limit production.

An incremental analysis of mill turn times was performed to illustrate how increases in average mill turn times may impact contractors at different points, depending on the amount of excess capacity available in their trucking system. The incremental analysis was first performed using an example contractor's system (Table 5.1) with two trucks, and drive times to and from the mill of 50 minutes. Average mill turn times were increased from 5 minutes to 70 minutes in 5-minute increments. The incremental analysis was repeated for the same contractor's system with drive times to the mill of 60 and 70 minutes respectively.

The incremental analysis revealed critical points for a given trucking fleet where increasing average mill turn time by only a few minutes can decrease the delivery capacity of the contractor's trucking system and cause the trucking system to limit total production. The exact point at which the decrease occurs depends on the contractor's drive time to the mill. When the contractor has excess capacity in their trucking system because of shorter drive times to the mill, turn times must increase substantially before they decrease the number of loads delivered per day (Figure 5.8).

Total costs per delivered ton increased (Figure 5.9) when mill turn times caused a decrease in the average number of loads delivered per day and the trucking system limited production from the harvesting system. The situations where total cost per delivered ton increased most rapidly correspond to the cases where the decrease in average loads produced per day limits production from the contractor's system.

Two minor "steps" or small cost increases occur as a result of production changes. For the 50 and 70-minute drive time scenarios a minor cost increase occurs where production decreases from approximately 7.2 loads per day where in-woods production is the limiting factor, to a level of production of 7 loads per day. The other slight increase occurs for all of the represented contractors after production has dropped to 6 loads per day. As a result of longer mill turn times, the trucking system reaches a point where production is limited to 5 loads per day on the first day of production, rather than 6 loads per day.

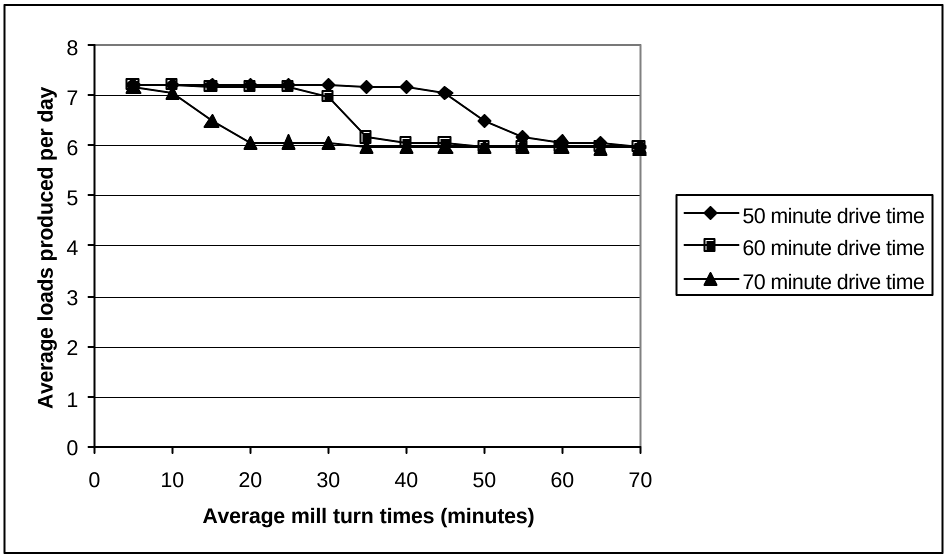

Figure 5.8 Average loads produced per day across three trucking scenarios as average mill turn time increases.

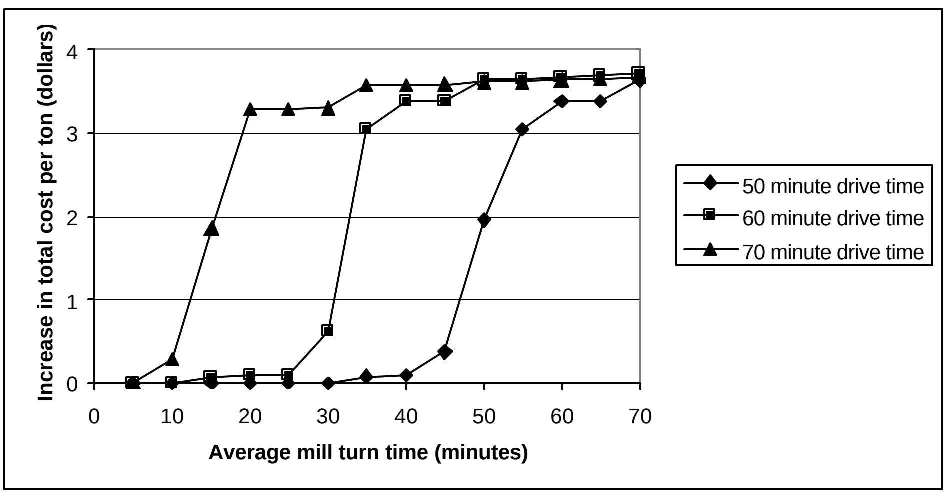

Figure 5.9 Increase in total cost per delivered ton across three trucking scenarios as average mill turn time increases.

The three examples of contractors with drive times to the mill of 50,60, and 70 minutes represented different levels of excess capacity in the trucking system before average mill turn times were increased incrementally. As with increasing drive times to the mill, the point at which the increased mill turn time became a limiting factor was different for each of the scenarios depending on the amount of excess capacity in their trucking system.

5.3 Impact of Delays at the Contractor's Landing

The amount of time required to load trucks at the contractor's in-woods landing is another part of the total round trip delivery time where delays can occur that decrease productivity from the contractor's trucking system. Delays may occur at the landing when an increased amount of time is required to load the truck or the truck is delayed because of an excessive amount of time required to merchandise wood.

To illustrate the impacts from increased time spent loading trucks, an incremental analysis of loading rates was performed using an example contractor setup (Table 5.1) with two trucks and drive times to and from the mill of 60 minutes. The merchandising rate was held constant at 50 tons per hour and the loading rate increased incrementally from 20 tons per hour to 100 tons per hour in increments of two tons per hour.

With a loading rate of 20 tons per hour (Figure 5.10) only 5 loads of wood are produced per day because the increased time trucks spend at the landing prevents some trucks from getting another load of wood near the end of the day. As the loading rate increases above 66 tons per hour, no additional production is gained. At loading rates above 66 tons per hour the trucking system was capable of delivering all wood produced from the harvesting crew and harvesting production became the limiting factor.

Truck loading delays at the landing result in more time spent at the landing per truck (Figure 5.11). Time at the landing per truck includes actual time being loaded, and idle time waiting to be loaded.

Delays can also occur at the landing when the merchandising rate becomes a bottleneck in the system. An incremental analysis was performed for the same example contractor's system (Table 5.1) with two trucks and a drive time to and from the mill of 60 minutes. The loading rate was held constant at 75 tons per hour, and the merchandising rate was increased to illustrate the impact that the merchandising rate can have on system productivity. The incremental analysis indicated that by the time the merchandising rate increased to 30 tons per hour, merchandising was no longer a constraint with this example system (Figure 5.12).

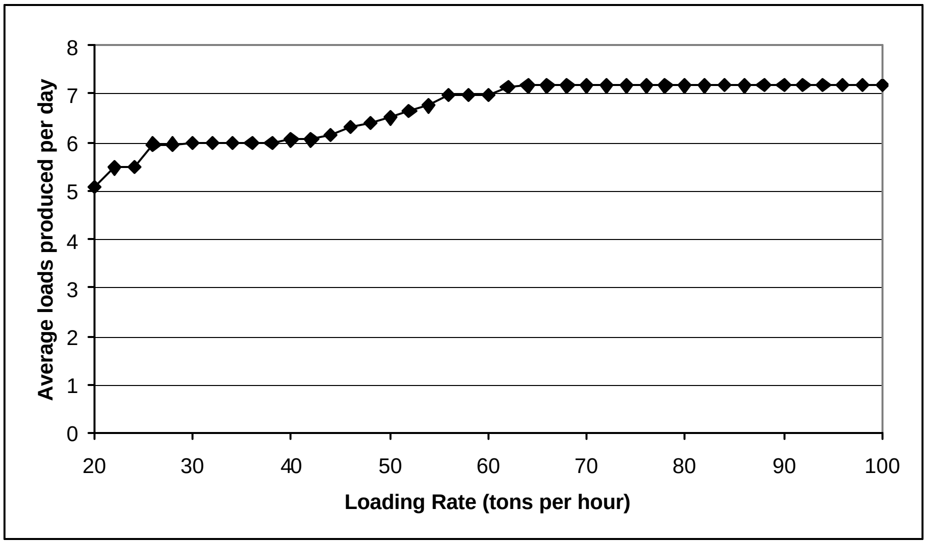

Figure 5.10 Change in average loads produced per day as the loading rate increases.

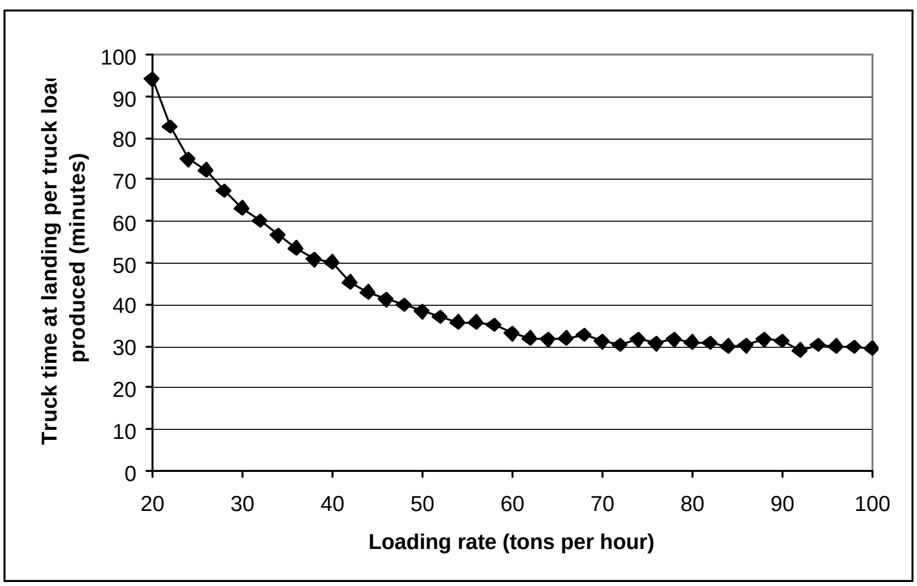

Figure 5.11 Average time trucks spend at the landing per truckload produced as the loading rate increases.

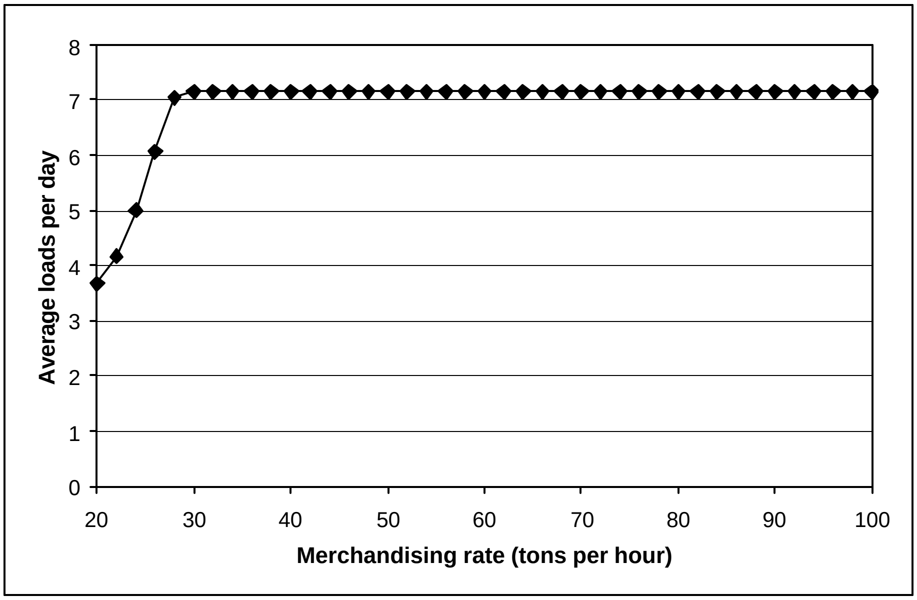

Figure 5.12 Average loads produced per day as the merchandising rate is increased.

5.4 Simulations to Illustrate the Impact of "Randomization"

The randomization feature of the model allows the model to illustrate impacts to the contractor's productivity associated with the random nature of truck delivery times. When a model simulation is performed without the randomization feature activated, each portion of the truck trip time uses the average value specified by the user. When the randomization feature is activated, instead of using the average time specified by the model user, times are randomly selected from a distribution of times that has approximately the same average as the value specified by the user.

To illustrate the impacts that variation in truck drive times and mill turn times can have on production outputs, stand harvests were performed with the LTSS model using an example contractor's production inputs (Table 5.1) with two trucks. The randomization feature of the model was activated and drive times to and from the mill were increased in one-minute increments between 55 and 78 minutes. The time segment between 55 and 78 minutes represents a segment of increased drive time to the mill where the example contractor's system is initially limited by harvesting production but shifts to being limited by the delivery capacity of the trucking system (Figure 5.1). A ΔT value of 1/60 was used in the model for an increased level of precision for recording the impacts associated with the random variations in the truck delivery times. The stand harvest was repeated 30 times at each one-minute drive time increment.

The model output values for average loads produced per day for each simulation were plotted (Figure 5.13) to show the range of values that occurred as the time increment increased. With a drive time of 55 minutes the example contractor was originally constrained by harvesting production at a production rate of approximately 7.2 loads per day. At the point where harvesting production is the limiting factor, randomization can not increase the average number of loads produced per day, but can potentially decrease production if significantly longer than average turn times are randomly selected. As the drive time increases so that trucking becomes a bottleneck, the range of average loads produced per day increases. The greatest range of outputs for average loads per day occurs at the transition between 6 and 7.2 loads per day.

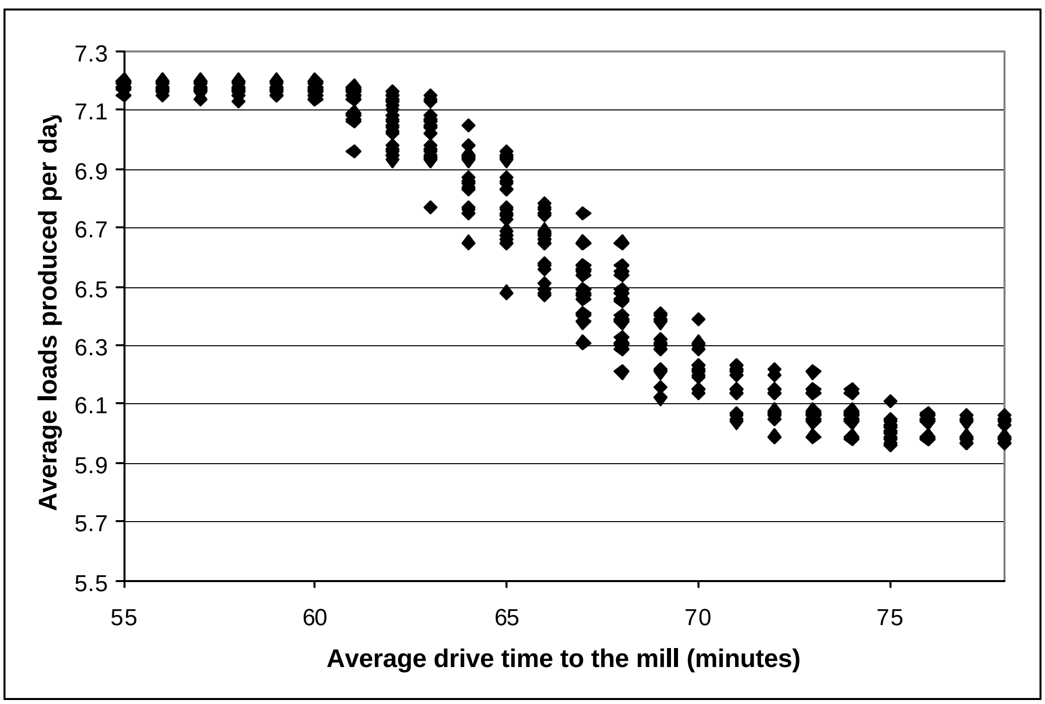

Figure 5.13 Average loads produced per day for 30 randomized simulations at each time increment between 55 and 78 minutes.

To compare results obtained with and without randomization, the simulation was performed over the same range of times without the randomization feature activated. The mean value of the 30 randomized simulations at each of the time increments was plotted along with the results obtained without randomization (Figure 5.14). The incremental analysis without randomization indicates a more pronounced transition between 64 and 69 minutes where trucking becomes a bottleneck and the average production drops to approximately 6 loads per day.

The line plotted for the average at each time interval of the randomized simulations illustrates that with the randomization feature activated there is not as sharp of a transition where trucking becomes a bottleneck and causes the trucking system to limit production. The randomized simulations suggest that the exact transition point where average production of the trucking system decreases by a load per day over the course of an entire stand harvest may not be as clearly defined as suggested by the previous non-randomized simulations.

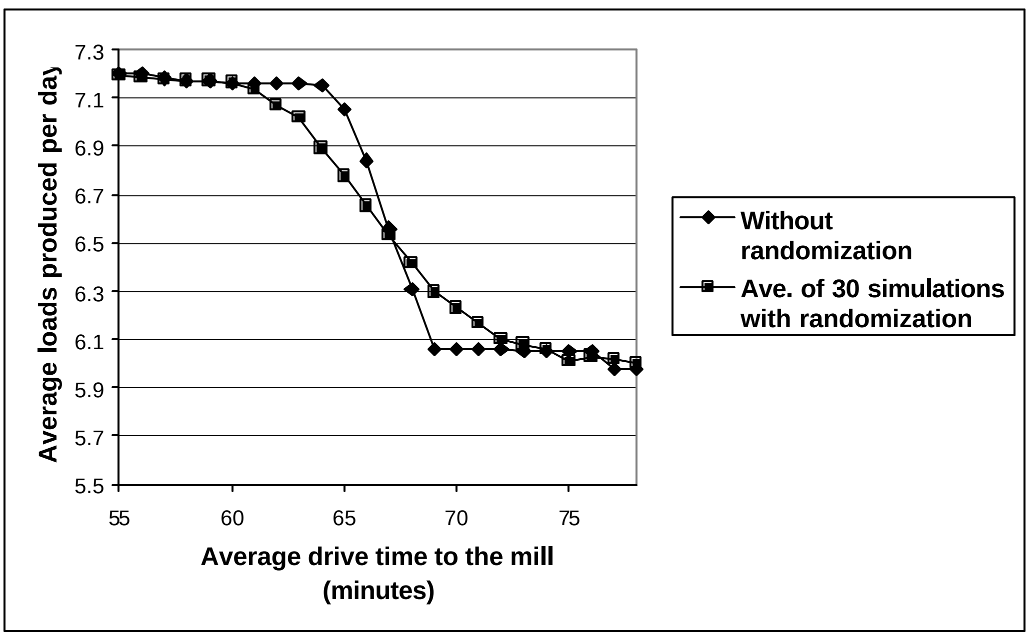

Figure 5.14 Average loads produced per day without randomization, and the average of 30 randomized simulations at each time increment.

5.5 Impacts of Multiple Product Sorts

In order for the LTSS model to be useful for examining contractor's systems where multiple products are harvested, the model was created with the capability to handle multiple product sorts at the landing. In the LTSS model, when only one product is sorted from wood skidded to the landing, that product can be loaded directly onto the first available truck. However, if multiple products are sorted at the landing, a decision must be made as to which product to load when a truck arrives at the landing. With multiple product sorts, the model assumes that a product cannot be loaded onto a truck until the amount of that product on the landing plus the amount expected to flow onto the landing in the next half-hour will equal a full truckload. Otherwise, situations may arise in the model where the truck cannot be completely loaded before the landing fills up with other products and the simulation shuts down. Therefore when multiple products are sorted from wood that flows onto the landing, a minimum amount of storage is required at the contractor's landing.

The exact minimum product storage required on the landing will vary depending on the specific product percentages as well as truck payloads. To illustrate the nature of the impacts associated with multiple product sorts, simulations were performed with increasing numbers of product sorts required. Production inputs for an example contractor's system (Table 5.1) were used with two trucks and an average drive time to and from the mill of 60 minutes for each product. Each product sort represented an equal percentage of the total stand size. For each product sort, the storage capacity at the landing was increased incrementally to find the minimum tons of product storage required to prevent a simulation shutdown as the landing filled up before a truck could be loaded (Table 5.2). The simulation was performed with the minimum storage, and then with storage capacity of 250 tons to illustrate possible production impacts caused by limited storage capacity at the landing.

Table 5.2 Results of example simulations to illustrate the impacts of multiple product sorts at the contractor's landing.

Number of sorts required	Percent of each product	Minimum storage required at landing (tons)	Average production at minimum storage (loads/day)	Average production at 250 tons storage (loads/day)	Total loads delivered
1	100	1	3.53	7.16	160
2	50	40	6.05	7.14	160
3	33.33	65	6.47	7.08	162
4	25	90	6.52	7.05	160
5	20	115	6.56	7.0	160
6	16.67	140	6.66	7.02	162
7	14.29	165	6.69	6.98	161
8	12.5	190	6.67	6.86	160

When only one product is sorted from wood harvested from the stand, the minimum storage capacity required on the landing to prevent the simulation from shutting down is one ton because when a truck arrives at the landing, wood can be loaded directly onto the truck. However with only one ton of storage space on the landing, almost as soon as the truck pulls away from the landing, production must stop because the one ton of available storage fills up. Once a truck arrives at the landing, production from the harvesting crew can resume. The increase in production from increasing storage at the landing is a result of the fact that after a truck departs, the harvesting crew can continue operating longer and wood is inventoried on the landing. When trucks arrive they can be quickly loaded from the inventoried wood and do not have to wait as wood arrives from the harvesting operation and is then merchandised before being loaded on the truck.

Even when storage capacity is not a limitation for the example contractor (250 tons of storage) average daily production tends to show a decreasing trend as the number of sorts increases. The decreasing trend is the result of the increased amount of time that trucks may have to spend waiting for enough of a particular product to complete their load, and from the fact that more wood remains inventoried on the landing at the end of the stand harvest. With more wood inventoried on the landing it takes longer to deliver the remaining wood after the harvest is completed therefore the number of days to complete the job increases.

Another impact from multiple product sorts is the increased number of truckloads delivered when 3,6, and 7 product sorts are required. The increased number of loads produced is the result of the fact that when the 4000-ton stand was divided equally into each of the product categories and then trucked away in 25 ton loads. The total tons of each product did not divide equally for 3, 6, and 7 product sorts and the last load of each product was less than a full truckload, therefore more total truckloads were required to deliver the entire stand.

5.6 Example of a Practical Application for the LTSS Model

The LTSS model was intended as a practical tool that could be used for predicting the magnitude of impacts that can occur to a logging contractor's system as a result of changes in the truck delivery system that impact the contractor's overall productivity. To illustrate an example of a practical use of the model, a simulation was performed using an example contractor's production and cost inputs (Table 5.1) with two trucks in the contractor's system. The first simulation was performed with a stand composed of 100% pulpwood and a drive time to and from the mill of 60 minutes. Next the simulation was repeated, assuming that the same contractor had moved to a new harvest site and had the same harvesting productivity, but instead of 100% pulpwood, the stand contained 90 percent pulpwood and 10 percent saw logs. However, now the contractor was further from the paper mill and it took 70 minutes to drive to and from the mill. Because of bridge weight restrictions on the way to the sawmill, it takes the driver 120 minutes to drive to the sawmill but the driver can make it back to the landing in 60 minutes. Average turn time at the sawmill is 30 minutes and 21 minutes at the pulp mill.

Outputs from the example simulations are reported in Table 5.3. With two trucks in the contractor's trucking fleet, when the contractor was moved to the second harvest location the model predicted that average total loads produced per day decreased from 7.16 to 5.99. The model estimated 26.3 tons of production lost per day as a result of the trucking constraint that caused the harvesting crew to go idle during the day. The model predicted that 0.4 additional trucks would be needed to maintain maximum production. To illustrate the impacts if the contractor had been operating three trucks instead of two, the number of trucks in the contractor's fleet was increased to 3 and the simulations were performed again.

Table 5.3 Results of simulations illustrating the model's use for predicting production changes when a contractor is moved to a new harvest location.

	Average loads produced per day	Harvest cost per ton ($)	Trucking cost per ton ($)	Total cost per ton ($)	Additional trucks needed	Estimated lost production (tons per day)
Original location 2 trucks	7.16	$15.55	$5.89	$21.44	0	0
Original location 3 trucks	7.20	$15.49	$8.79	24.28	0	0
New location with 2 trucks	5.99	$17.90	$7.05	$24.95	0.4	26.3
New location with 3 trucks	7.17	$15.53	$8.84	$24.37	0	0

The example simulations illustrated that when moved to the new location, with only two trucks in the trucking fleet, the contractor was not able to keep up with harvesting production because of increased drive times and as a result of the lost production, total costs per ton increased. When the simulation was performed at the original location with 3 trucks in the contractor's fleet, harvesting costs changed very little but trucking costs increased because the extra truck represented an added expense but resulted in very little increased production. However, when the simulation was performed again at the new location with 3 trucks in the contractor's fleet, harvesting costs per ton decreased because trucking no longer limited production. However, trucking costs per ton increased because with the 3 trucks there was excess trucking capacity in the system and on average each truck did not haul as many loads. Total costs per ton at the new harvest location decreased by adding the additional truck.

CHAPTER 6 SUMMARY AND CONCLUSIONS

Stella® systems modeling software was used to build a generalized computer simulation model of a logging contractor's log trucking system. The Log Trucking System Simulation model (LTSS) was designed to illustrate the magnitude of impacts to a logging contractor from imbalances in the trucking and harvesting systems as a result of changes in the total truck turn times. The model operates at a generalized level to illustrate the relative magnitude of impacts to the contractor without requiring extensive data collection for production and cost inputs to operate the model. The model represents a forest harvesting and transportation system that has been previously simulated by others (Goulet et. al, 1979). However, instead of focusing on the harvesting system and predicting production rates from the in-woods harvesting crew and machinery, the LTSS model focuses on impacts that can occur when changes in the contractor's truck delivery system impact harvesting productivity. The LTSS model requires less detailed inputs than required by many harvesting simulation models, which attempt to predict production for the in-woods harvesting system, or attempt to predict the precise costs incurred by the contractor. While production and cost inputs are less intensive than some previous models, the LTSS model can allow the user to simulate more complexity in the trucking delivery system. The LTSS model allows multiple product sorts, where each product has its own mill destination and turn times, as well as different average truck payloads for each product.

The model predicts productivity of the trucking system in average loads delivered per day based on the total round trip delivery time for log trucks. The LTSS model is capable of illustrating impacts from increased time spent by trucks in all segments of the round trip delivery time. The total round trip delivery time consists of the loading time at the in-woods landing, driving loaded to the receiving mill, mill turn time, and the return trip unloaded. The number of loads per day the trucking system can deliver will either be limited by production from the harvesting system or from increased time spent in the round trip delivery process. Increased delivery times limit the loads delivered per day when trucks do not have time to return to the in-woods landing and get another load of wood before the end of the scheduled day for the harvesting crew.

The model was used to perform incremental analyses to illustrate the nature of impacts to the logging contractor's production caused by changes in the trucking system. When a contractor's trucking system has excess delivery capacity, increases in total trip times do not result in decreased production, but simply allow trucks less idle time at the landing and more time for delivering wood. As delivery times increase, excess trucking capacity is lost and a critical point is reached where increasing average turn times by only a few minutes can result in the loss of a load of wood per day that the truck is capable of delivering. As a result the number of loads per day a trucking system can deliver decreases in a stair step-like pattern.

The model illustrated that the primary impacts to logging contractor's costs and productivity associated with truck turn times results when the increased time decreases the number of loads per day the trucking system can deliver and causes the delivery capacity of the trucking system to limit the contractor's total production. Harvesting crew utilization and harvesting productivity decrease as a result of the inability of the trucking system to keep up with the harvesting system. As delivery times increase to the point that the trucking system can't keep up with the harvesting system, additional trucks must be added to the contractor's trucking fleet to maintain maximum production from the harvesting crew.

Incremental analyses illustrated that for a range of total trip times to the mill that theoretically there is an ideal size trucking fleet that allows a contractor to operate at least cost. The ideal truck fleet for a contractor to operate is the number of trucks that result in the least total cost per ton for a given total trip time to the mill. When production from the harvesting system is the limiting factor, adding additional trucks simply adds extra costs and no additional production is gained. However when trucking is the limiting factor, adding additional trucks can result in decreased total cost per ton as the total system production is increased.

Potential impacts from variations in truck turn times were illustrated using the randomization feature of the LTSS model. The randomization feature was activated and repeated simulations were performed in an incremental analysis across a range of drive times to the mill that represented a transition where the contractor's system went from being limited by harvesting production to being limited by trucking production. The analysis indicated that with randomization the transition where average production decreased by a full truckload per day was less abrupt than without random variations in turn times.

The model indicated that requiring multiple product sorts at the landing could impact the contractor's system productivity. An example simulation indicated that as more product sorts are required, larger storage capacities at the landing are necessary to prevent the simulation from shutting down as the landing fills up before a truckload can be completed. Requiring multiple product sorts can lead to decreased average daily productivity as a result of increased inventory stored on the landing and increased idle time trucks spend waiting for enough of a product to complete truckload.

While the exact point at which an increase in mill turn times will cause the loss of production from the contractor's trucking system depends on the individual contractor's system, the receiving mill is one point through which trucks from many contractor's systems must pass through. Even though a specific average mill turn time may not impact a contractor's system with excess trucking capacity, the same turn time may be enough to cause another contractor to lose a load of production per day. Efforts to minimize the overall mill turn time may increase the efficiency of the system as a whole.

The LTSS model provides the user a tool for predicting the magnitude of cost and productivity changes to a logging contractor based on changes in the contractor's trucking system. The model could allow a forester or a logging contractor to evaluate the impacts to the contractor's production based on moving to a new harvest location with different trip times to the mill. The model could also be useful for decision making regarding allocation of stand harvests among different contractors in an area where it could help identify the adequacy of a contractor's trucking system based on drive times to the different mills where products would be trucked to.

The model illustrated that for an individual contractor's trucking system there is a range where turn times can increase but will not impact the total number of loads per day the contractor can deliver. A point is then reached where even a minor increase in trip times will decrease production by a load per day. The LTSS model could be useful in identifying contractors who would be most likely impacted by increases in turn times. Giving priority to trucks from those contractor's systems and moving them through the mill as quickly as possible could potentially increase the productivity of the contractors at critical points in their delivery system without decreasing the overall productivity of the other contractor's trucking systems.

The model user should keep in mind the model's limitations with the assumption of a known constant rate of harvesting production, and that the actual costs incurred by a logging contractor can be far different than the cost inputs used for the model. The model does not begin to cover all of the possible human, environmental, and mechanical interactions that can cause system variability and changes in production for a logging contractor's system on a day-to-day basis. However, the LTSS model is a tool that can be utilized with relatively simple input data to examine the operations of logging contractor and illustrate the magnitude of impacts that can occur as the logging contractor's trucking system affects overall system costs and productivity.

Suggestions for Future Research in This Area

1. For the purposes of investigating the impacts associated with the contractor's trucking system, this model assumed a known constant rate of harvesting production. In actual harvesting systems, wood does not arrive at the landing at a

constant rate and can vary significantly from day to day and from tract to tract. Future research could focus on expanding the model to predict production from the harvesting system and investigate the impacts to the contractor's system associated with variations in harvesting production. The LTSS model could be a more valuable tool if it could be combined with readily obtained predictors of harvesting production rates, that would allow it to predict harvesting production rates without requiring excessive amounts of data collection to operate the model. In addition the model could be expanded to include more realistic harvesting conditions such as including multiple landings for a stand harvest, including mill quotas, and including the hours when mills accept wood into the decision for which product to load onto a waiting truck.

2. Further studies could also be directed towards expanding the LTSS model to investigate the costs and benefits associated with the ways in which contractors attempt to separate in-woods harvesting production from the trucking system. This model dealt only with a "hot" harvesting operation where empty trucks must be loaded at the in-woods landing and then drive to the mill. If the truck could not make it back to the landing before the in-woods crew left, then it could not get another load. Some logging contractors deal with this situation by using a system of "set out" trailers where unloaded trailers are dropped off at the landing to be loaded at the operator's convenience. A "spotting truck" at the in-woods landing shuttles the trailers between the landing and a convenient roadside drop off point. With a set out trailer system the loaded trailers can be picked up at any time, not just when the in-woods crew is working.

3. Another possible area for future research could be investigation of ways for logging contractors to deal with the fact that with a fixed number of trucks in their fleet the contractors total delivery capacity changes with every move to a new harvest site where driving times to receiving mills change. Incremental analyses with the LTSS model illustrated an ideal size trucking fleet for a range of drive times that allowed the contractor to operate at least cost. However an ideal size

trucking fleet for one harvest site, may be underutilized or may limit production if round trip delivery times or harvesting production changes on the next tract to be harvested.

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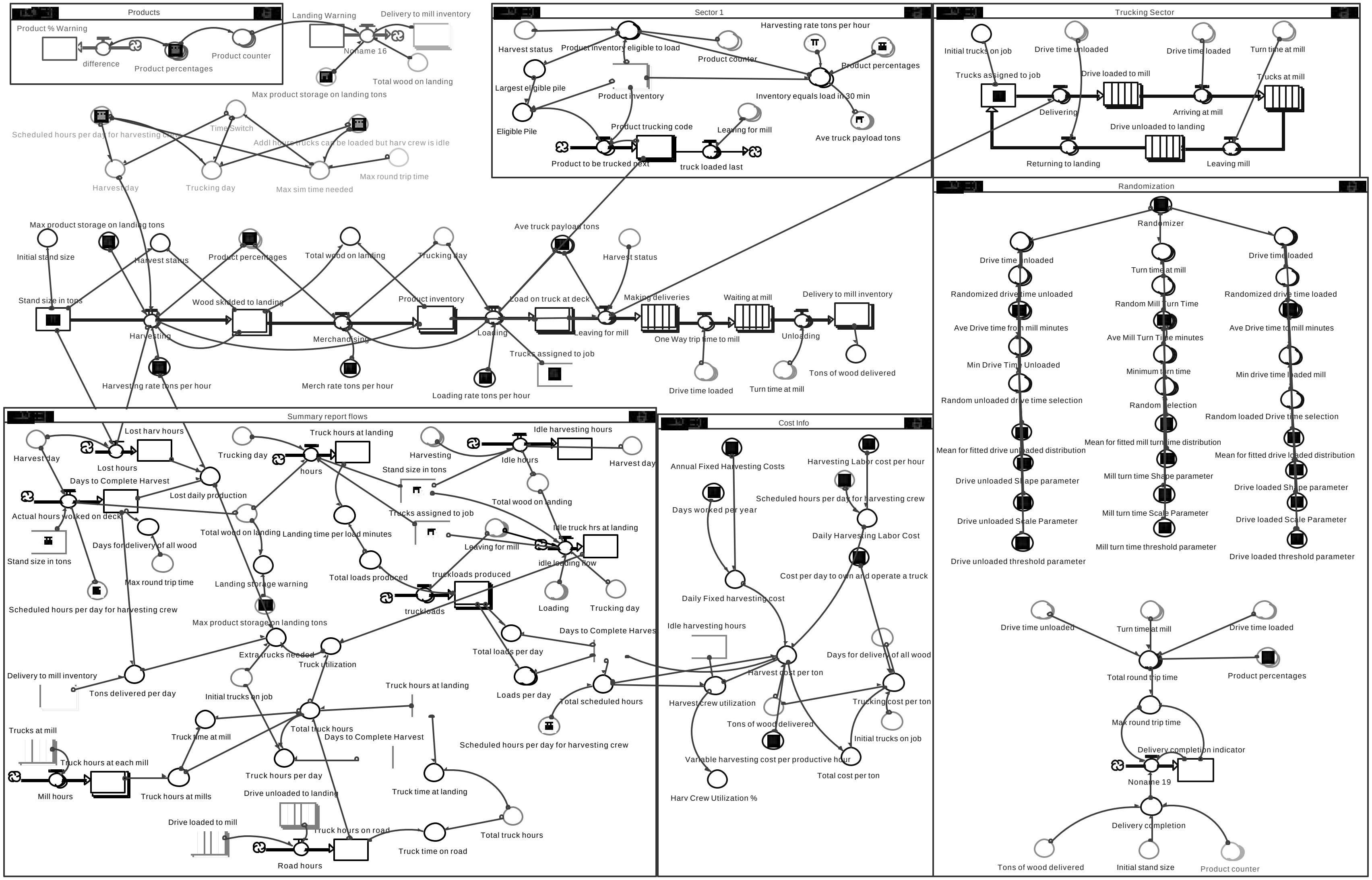
Appendix A Complete LTSS model layout.



Appendix B Example of possible cost input ranges for typical contractor's systems in the Appalachian region.

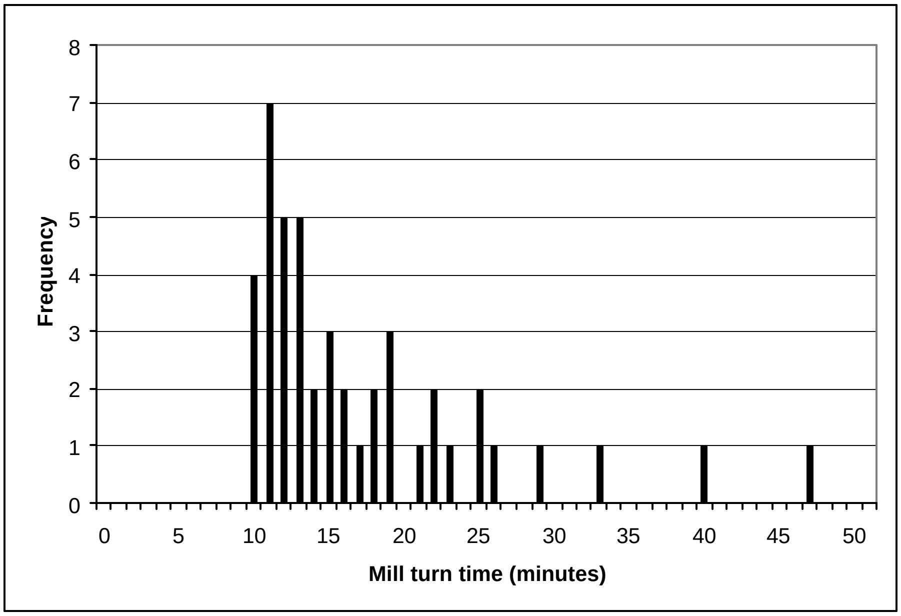
	INWOODS COST RANGES	
SYSTEM ONE	HIGH / NEW	LOW / USED
One Timber Cutter, Chainsaw One Skidder One Loader w/ Bucksaw Dozer, Support Vehicles, Overhead		
ANNUAL FIXED	$130,000	$65,000
LABOR COST PER HOUR (4 to 5 men)	$100	$55
VARIABLE COST PER HOUR	$45	$35
REALISTIC PRODUCTION RANGE		
LOADS PER DAY	5	2
TONS PER DAY	135	55

SYSTEM TWO	HIGH / NEW	LOW / USED
Three Timber Cutters, Chainsaw Two Skidders or setout machines One Loader w/ Bucksaw Dozer, Support Vehicles, Overhead		
ANNUAL FIXED	$165,000	$90,000
LABOR COST PER HOUR (6 to 8 men)	$160	$80
VARIABLE COST PER HOUR	$70	$55
REALISTIC PRODUCTION RANGE		
LOADS PER DAY	7	5
TONS PER DAY	190	135

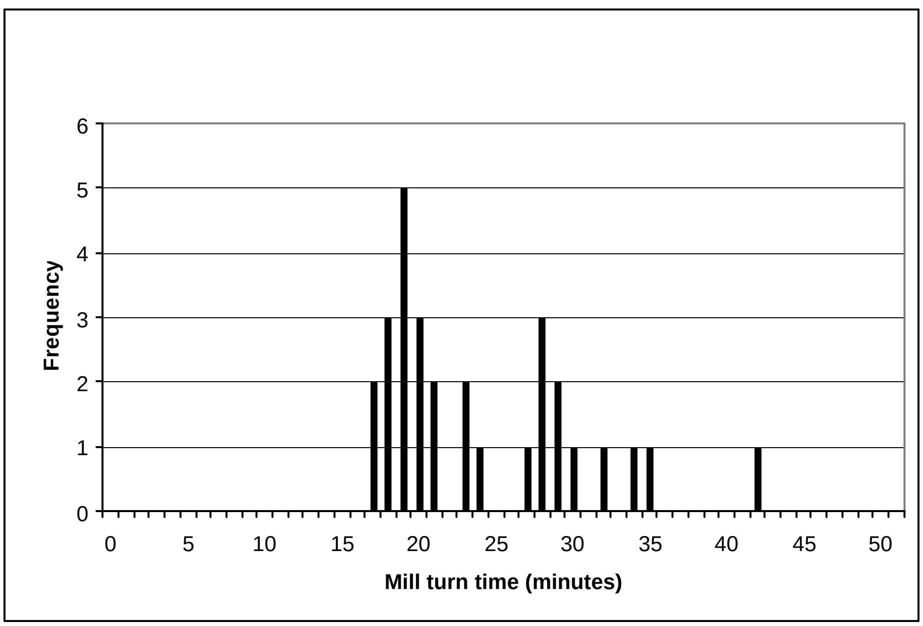
SYSTEM THREE	HIGH / NEW	LOW / USED
Mechanized Cutting & Processing Multiple Skidders &/or Setouts Mechanized Loading Dozer, Support Vehicles, Overhead		
ANNUAL FIXED	$400,000	$155,000
LABOR COST PER HOUR	$180	$100
VARIABLE COST PER HOUR	$160	$120
REALISTIC PRODUCTION RANGE		
LOADS PER DAY	10	7
TONS PER DAY	270	190

Daily Cost To own and operate a truck		
	HIGH / NEW	LOW / USED
DOLLARS PER DAY	$525	$275

Appendix C Histograms of mill turn times for mills two and three.

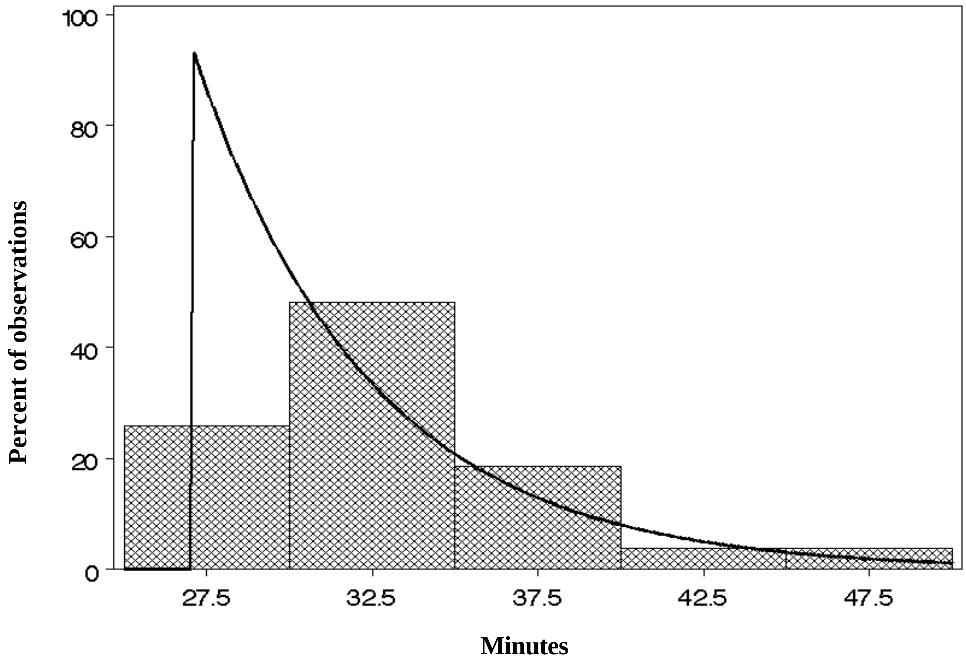


Appendix C Figure 1 Histogram of turn-times for mill number two (N=45).

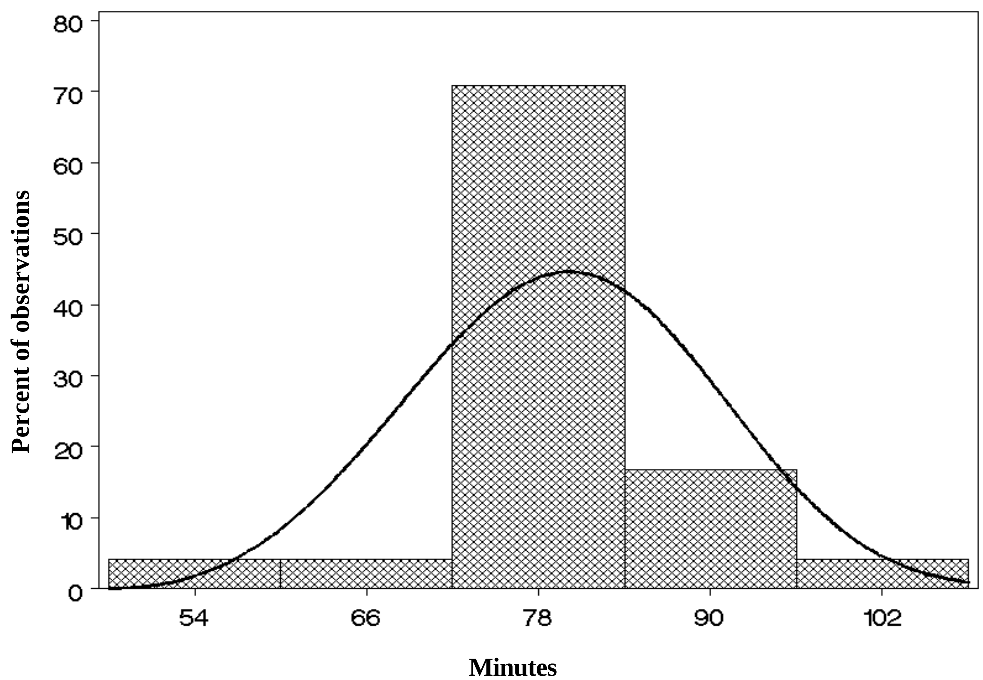


Appendix C Figure 2 Histogram of turn-times for mill number three (N=29).

Appendix D Default distributions for drive times loaded and unloaded.

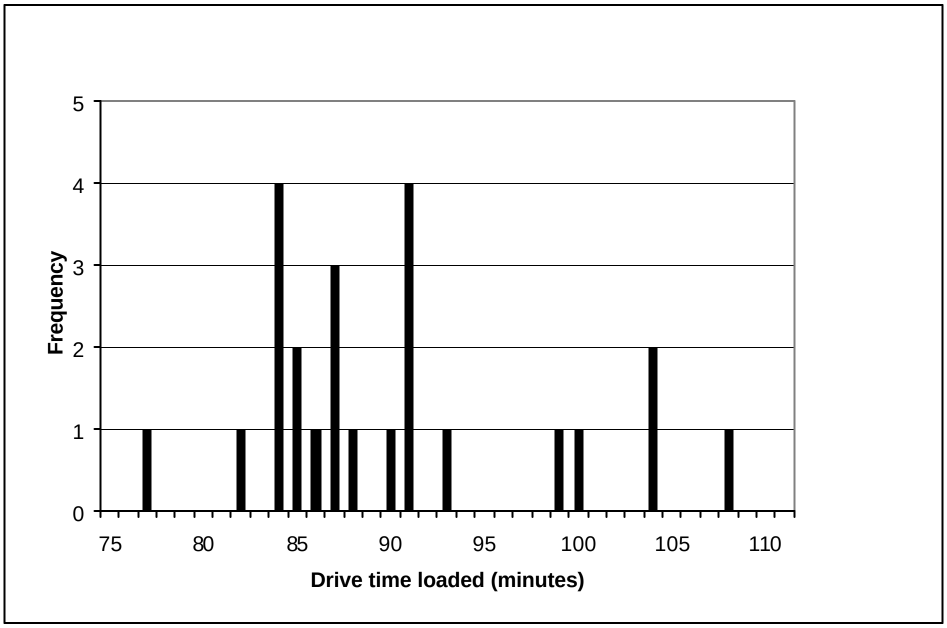


Appendix D Figure 1 Default Weibull distribution for drive times loaded to the mill (N=27).

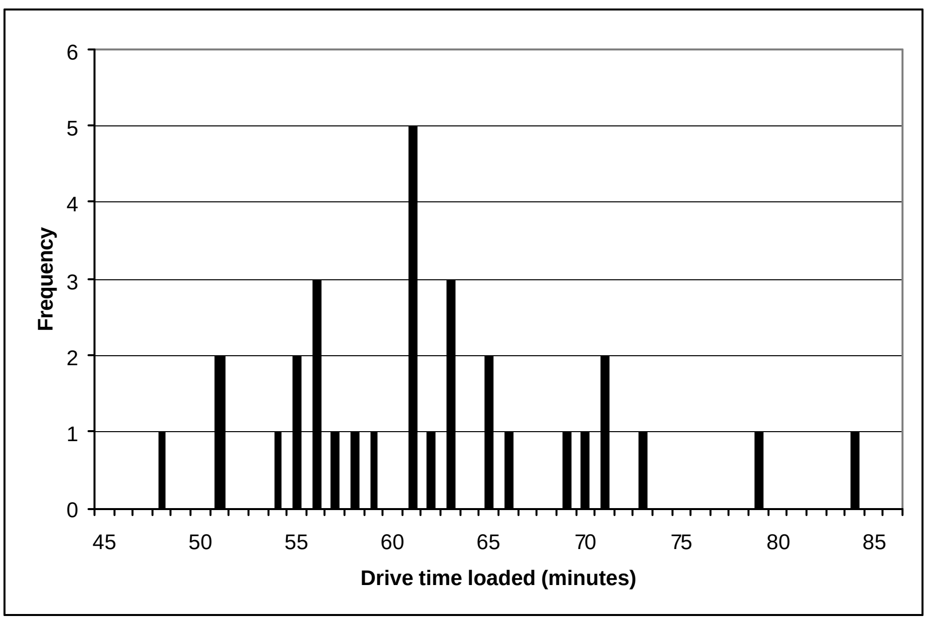


Appendix D Figure 2 Default Weibull distribution for drive times unloaded (N=24).

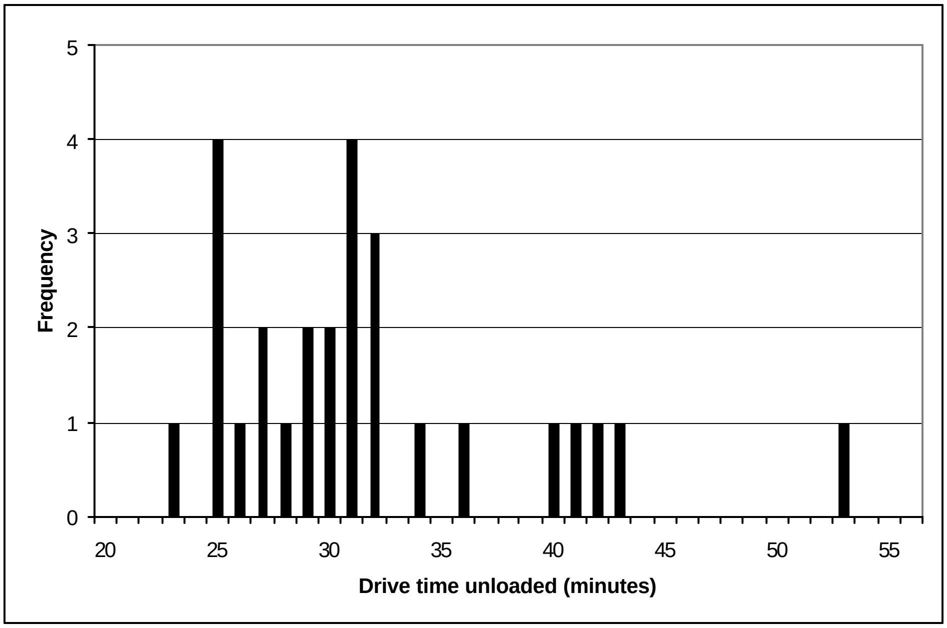
Appendix E Additional truck drive time distributions.



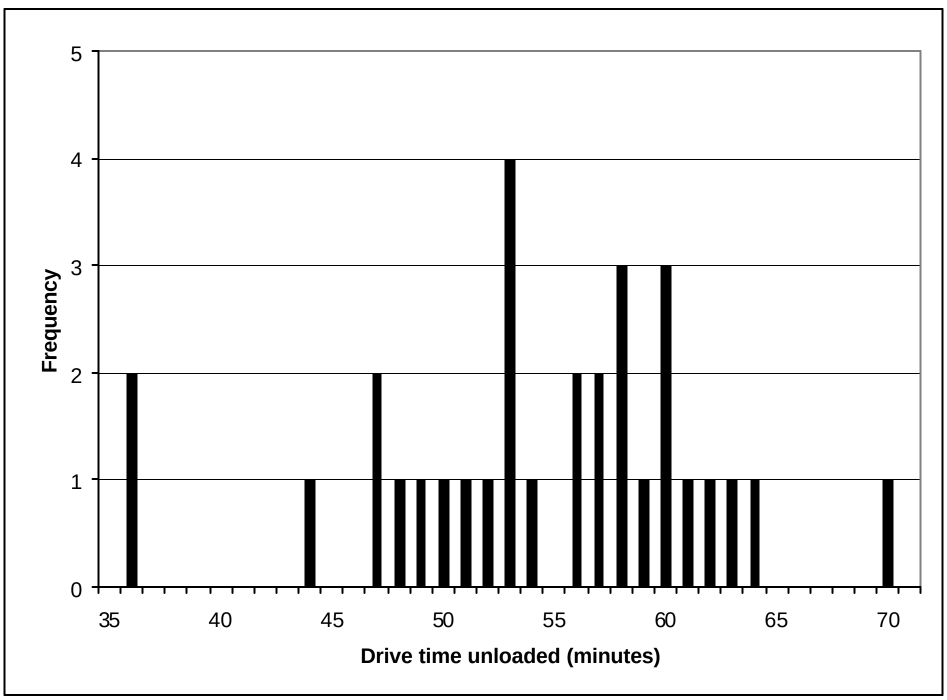
Appendix E Figure 1 Histogram of drive times loaded to the receiving mill (N=24).



Appendix E Figure 2 Histogram of drive times loaded to the receiving mill (N=31).



Appendix E Figure 3 Histogram of drive times unloaded from the mill to the landing (N=27).



Appendix E Figure 4 Histogram of drive times unloaded from the mill to the landing (N=31).

Appendix F Work-sample test input data.

Contractor observation	Sched. Hours	Harv. rate	Merch rate	Load. Rate	Trucks	Payload	Product	Product percent	Drive times to & from mill	Mill turn time	Loads hauled	Loads prod.	Loads pred.
A	9.2	9.78	54.06	49.15	1	30	HST	33.33	34.5	21	1		1
							OSB	33.33	101	21	1		1
							HPW	33.33	9.9	21	1		1
										TOTAL	3	3	3
B	9.2	9.57	40.29	52.38	1	22	HPW	75	46.5	21	3		2.98
							HST	25	49	21	1		1
										TOTAL	4	4	3.98
C	9	10.67	44.93	58.41	2	24	HPW	75	79.5	21	3		3
							HST	25	48	21	1		1.01
										TOTAL	4	4	4
D	8.5	16.24	63.78	36.45	4	23	HPW	83.33	79.5	21	5		4.98
							PPW	16.67	79.5	21	1		1
										TOTAL	6	6	5.97
E	8.2	15.61	42.65	63.97	2	32	HPW	75	138	21	3		2.96
							HST	25	41.1	21	1		1.01
										TOTAL	4	4	3.97
F	9	20.83	55.2	77.29	4	25	HPW	62.5	66	21	5		4.66
							HST	12.5	38.1	21	1		0.93
							POLE	25	57	21	2		1.86
										TOTAL	8	7.5	7.45
G	6.7	20.9	66.87	59	2	28	HPW	83.33	40.5	21	5		4.18
							HST	16.67	103.5	21	1		0.84
										TOTAL	6	5	5.01
H	10	9.6	80.5	48.3	2	32	HPW	83.33	66	21	5		2.51
							HST	16.67	8.5	21	1		0.5
										TOTAL	6	3	3.01
I	8.7	24.83	46.55	93.1	4	27	HPW	71.43	138	21	5		5.62
							HST	28.57	137.49	21	2		2.28
										TOTAL	7	8	7.91
J	9.5	18.42	58.89	125.1	3	25	HPW	83.33	52.5	21	5		5.85
							HST	16.67	64.5	21	1		1.18
										TOTAL	6	7	7.03
K	9	22.22	82.54	96.3	3	25	HPW	85.71	57.3	21	6		6.88
							HST	14.29	68.4	21	1		1.15
										TOTAL	7	8	8.03
L	9	12.89	31.68	70.39	1	29	HST	33.33	48.5	21	1		1.35
							HPW	66.67	10.5	21	2		2.66
										TOTAL	3	4	3.98
M	9	8.86	35.16	82.05	1	29	HPW	50	104.1	21	1		1.36
							HST	50	90	21	1		1.36
										TOTAL	2	2.75	2.72
N	10	25.76	62.58	71.96	2	30.3	HPW	100	43.8	21	5		8.48
										TOTAL	5	8.5	8.48
O	8.75	25.76	50.56	85.31	2	30.3	HPW	80	40.8	21	4		5.85
							HST	20	39.5	21	1		1.56
										TOTAL	5	7.5	7.48
P	9.1	20.44	55.88	77.37	3	24	HPW	71.43	110	21	5		5
							HST	28.57	53.1	21	2		2
										TOTAL	7	7.75	7
Q	8.7	27.93	52.73	164	4	27	HST	100	139.8	21	7		8
										TOTAL	7	9	8
R	8.5	9.71	47.4	43.09	1	22	HST	33.33	52.5	21	1		1
							HPW	66.67	87.9	21	2		2
										TOTAL	3	3.75	3
S	9	16	27.74	71.67	1	32	HPW	67	69	21	2		2.71
							HST	33	8.9	21	1		1.35
										TOTAL	3	4.5	4.06
Average	8.90	17.16	52.63	75.02	2.26								

VITA

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