

Systems Dynamics Simulation To Improve Timber Harvesting System Management

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(ABSTRACT)

Two computer simulation models were developed to address harvest system - stand assignment and wood flow variability problems in the southeast United States.

The Harvest System Assignment (HSA) model is used to evaluate the impact of a particular stand assignment on harvest system effectiveness and is designed to assist with harvest system assignment decisions. Four general harvesting systems: manual, mechanized, shovel and cut-to-length can be modeled to harvest timber, from standing trees to processed logs loaded on to trucks. Model testing showed that as terrain, tract and system characteristics changed, the effectiveness of each of the four systems varied. The most effective system can be determined for any combination of terrain, tract and system characteristics. The model output shows production potential as well as cost per unit, and identifies the causes and magnitude of inefficiency.

The Machine Allocation (MA) model is used to evaluate the potential of a given machine combination and is designed as a research tool to investigate the cause and impact of machine interactions. This model has a defined system structure and can incorporate up to five machines for each of three phases in the harvesting operation: felling, skidding and processing. Particular system configurations can be evaluated and possible improvements to machine combination determined.

The HSA model is a widely applicable tool that will be available for industry in the southeastern United States. It has utility for training of personnel and for operational use. The MA model is a detailed tool that will be used in a research capacity to advance harvesting system management.

CONTENTS

(ABSTRACT).....	ii
CONTENTS.....	iii
LIST OF FIGURES	vii
LIST OF TABLES.....	viii
CHAPTER 1. INTRODUCTION	1
1.1 Objectives	2
CHAPTER 2. LITERATURE REVIEW	4
2.1 Existing Forest Harvesting Models.....	4
2.1.1. Georgia Tech Model (1968).....	4
2.1.2. Auburn Pulpwood Harvesting System Simulator (1969)	4
2.1.3. Timber harvesting model for Appalachia (1973).....	5
2.1.4. Simulation Applied to Logging Systems – SAPLOS (1973).....	5
2.1.5. Appalachian Logging Simulator (1973)	6
2.1.6. Forest Harvesting Simulation Model – FHSM (1975)	6
2.1.7. Timber Harvesting and Transportation Simulator – THATS (1975).....	7
2.1.8. Full-Tree Chipping and Transport Simulator - FCTS (1976).....	7
2.1.9. Harvesting System Simulator – HSS (1976)	8
2.1.10. Residues for Power – REPO (1976)	8
2.1.11. Harvesting Analysis Technique – HAT (1981)	9
2.1.12. Program For Logging Cost Estimation – PROLOG (1982)	9
2.1.13. Geometric Modeling Of Thinning System Performance (1983)	10
2.1.14. Model for predicting logging machine productivity (1983)	10
2.1.15. Logging Cost Analysis Package – LCAP (1984)	10
2.1.16. Auburn Harvesting Analyzer – AHA (1985).....	11
2.1.17. Harvesting System Analyzer – HSA (1985).....	11
2.1.18. Interactive Simulator for Studying the Design of Feller-Bunchers (1985).....	12
2.1.19. Tree Harvesting Simulator – TREESIM (1986).....	12
2.1.20. Operator Variability In Interactive Feller-Buncher Simulation (1987)	13
2.1.21. Discrete State, Continuous Parameter Markov Process Harvesting System Analysis (1988).....	13
2.1.22. Animated Mechanized Tree Feller Interactive Simulator (1990).....	13
2.1.23. Timber Harvesting Analyses and Design Using Simulation (1990).....	14
2.1.24. Ground Based Harvesting System Simulation – GB-SIM (1993).....	14
2.1.25. Harvester-Forwarder Softwood Thinning Simulation (1995).....	15
2.1.26. Stand, Harvest, and Equipment Interactions (1998)	15
2.1.27. Simulation of a Single-Grip Harvester (1999).....	16
2.1.28. Bundle Distribution and Skidder Assignment (2001).....	16
2.2. Types of Forest Harvesting Models.....	17
2.2.1. Scope.....	17
2.2.2. Simulation Method.....	19
CHAPTER 3. STELLA® SOFTWARE.....	21
CHAPTER 4. HARVEST SYSTEM ASSIGNMENT (HSA) MODEL.....	24
4.1. Objective	24

4.2.	Scope.....	24
4.2.1.	Manual chainsaw felling and cable skidding system.....	27
4.2.2.	Mechanized felling and grapple skidding system.....	28
4.2.3.	Shovel bunching and grapple skidding system.....	28
4.2.4.	Cut-to-Length harvesting and forwarding system	29
4.3.	Structure.....	29
4.4.	Inputs.....	32
4.4.1.	Cost inputs	34
4.4.2.	Input Assumptions	34
4.5.	Productivity calculation	35
4.6.	Delays	35
4.6.1.	System delays.....	35
4.6.2.	Landing storage delays	37
4.7.	Simulation length.....	37
4.8.	Outputs.....	39
4.8.1.	Productivity.....	39
4.8.2.	Efficiency.....	39
4.8.3.	Cost calculation.....	40
CHAPTER 5.	MACHINE ALLOCATION (MA) MODEL.....	42
5.1.	Objective.....	42
5.2.	Scope.....	42
5.3.	Structure.....	44
5.4.	Inputs.....	45
5.4.1.	System inputs.....	46
5.4.2.	General Inputs.....	46
5.5.	Simulation calculations.....	47
5.5.1.	General input parameter calculation	47
5.5.2.	Skidder assignment	48
5.5.3.	Productivity Calculation	49
5.5.4.	Decision to Add/Remove Machines	50
5.5.5.	Machine Interactions.....	58
5.5.6.	Machine Delays	59
5.6.	Simulation Length.....	60
5.7.	Outputs.....	62
5.7.1.	Productivity.....	62
5.7.2.	Delay/Interaction Summary	62
5.7.3.	Machine allocation and substitution	63
CHAPTER 6.	MODEL VALIDATION	64
6.1.	HSA Model	64
6.1.1.	Site Ranking.....	65
6.1.2.	System Comparison Ranking.....	65
6.2.	MA model	66
6.2.1.	Machine Reallocation	66
6.2.2.	System Comparison	67
6.2.3.	Case study #1: Tigercat productivity study (Visser and Stampfer 2000) .	68

6.2.4. Case Study #2: Comparison of Mechanized Systems for Thinning Ponderosa Pine and Mixed Conifer Stands (Hartsough et al. 1997).....	72
CHAPTER 7. EXAMPLE SIMULATIONS	77
7.1. HSA Model	77
7.1.1. Impacts of skid distance on the harvesting system	78
7.1.2. Impacts of site parameters on the harvesting system.....	80
7.1.3. Example of Practical Application of the HSA model.....	88
7.2. MA Model.....	93
7.2.1. Unbalanced system	93
7.2.2. Machine substitution.....	117
7.2.3. Skidder Assignment.....	121
7.2.4. Example of practical application of MA model.....	123
CHAPTER 8. SUMMARY AND CONCLUSIONS	125
8.1. Harvest System Assignment Model.....	125
8.1.1. Opportunities for further research.....	127
8.2. Machine Allocation Model	127
8.2.1. Opportunities for further research.....	129
REFERENCES	130
APPENDIX 1: HSA Production Functions	135
Function form.....	135
Sources of production functions:	136
Mechanized Harvesting System.....	137
Effect of Piece Size.....	137
Effect of Stocking	137
Effect of Slope	137
Effect of Harvest Intensity	137
Effect of Skid Distance	137
Manual Felling Cable Skidding Harvest System.....	138
Effect of Piece Size.....	138
Effect of Stocking	138
Effect of Harvest Intensity	138
Effect of Skid Distance	138
Shovel Bunching/Forwarding Harvesting System.....	139
Effect of Piece Size.....	139
Effect of Stocking	139
Effect of Slope	139
Effect of Harvest Intensity	139
Effect of Skid Distance	139
Cut-to-Length Harvesting System	140
Effect of Piece Size.....	140
Effect of Stocking	140
Effect of Slope	140
Effect of Harvest Intensity	140
Effect of Skid Distance	140
APPENDIX 2: MA PRODUCTION FUNCTIONS.....	141
Feller-buncher	141

Harvester	141
Motor-manual chainsaw.....	141
Forwarder	142
Grapple Skidder	142
Cable Skidder.....	142
Processor	142
Motor-Manual Processing.....	142

LIST OF FIGURES

Figure 4.1: Harvesting system scope.	25
Figure 4.2: Production function for a system.....	26
Figure 4.3: Schematic Diagram of HSA model showing system selection, productivity calculations and delay function.....	31
Figure 4.4: Example HSA model delay length function in the Stella programming environment	36
Figure 4.5: Coefficient of Variation at different simulation lengths for manual system with site, stand and system parameters set at default values. CV constructed from 10 runs at each level of simulation length.	37
Figure 4.6: Comparison of the effect of run length and number of runs on the relative spread of the 95 percent confidence interval	38
Figure 5.5.1: Production potential frontier for a harvesting system	43
Figure 5.5.2: MA model schematic diagram	44
Figure 5.3. Effect of calculation interval (shown as Iterations per Minute) or DT on the coefficient of variation. Fewer iterations per minute results in longer calculation interval.	61
Figure 7.1: Productivity of the four harvesting system types in the HSA model as a function of Maximum Skid Distance.....	79
Figure 7.2: Piece size productivity curves by harvesting system type over a range of DBH values with all other parameters set to default values.....	80
Figure 7.3: Cost per unit (\$/ton) for the four harvesting system types defined in the HSA model over a range of DBH values with all other parameters set to default values.	81
Figure 7.4: Lowest cost frontier for all harvesting system types over a range of DBH values with all other parameters set at the default level.	82
Figure 7.5: Impact of Slope parameter on Cost of Inefficiency for each of the four harvesting systems in the HSA model.	83
Figure 7.6: Cost of Inefficiency by harvesting system for default parameter values.	84
Figure 7.7: Parameterized Cost of Inefficiency for manual harvesting system – Slope values varied while all others set to default values (Table 7.1, Table 7.2).....	86
Figure 7.8: Parameterized Cost of Inefficiency cut-to-length system – Slope values varied while all others set to default values (Table 7.1, Table 7.2).	87
Figure 7.9: System harvesting costs per ton for practical application of HSA model example simulation	91
Figure 7.10: Harvest system cost of inefficiency ton for practical application of HSA model example simulation	92
Figure 7.11: Effect of number of Dynamic-Fixed assignment methods on system productivity	122

LIST OF TABLES

Table 5.5.1: Machine types. For each of the three phases of the harvesting operation incorporated in the MA model there are two or more machine types available.	46
Table 6.1: Ranking scoring schedule for validation of HSA model. “Ranking difference” is the variation in rank place between published studies and HSA model output. “Score” is the score associated with each “ranking difference.”	65
Table 6.2. Ranking scoring example.....	65
Table 6.3: Ranking validation scores for site ranking of harvesting systems.....	65
Table 6.4: Ranking validation scores for system ranking of harvesting systems	65
Table 6.5: Average percentage deviation of estimated from actual productivity by machine phase, add/remove machine and total. Positive value represents overestimate, negative value represents underestimate.	66
Table 6.6: Productivity (tons/PMH) of system phases for the Tigercat and associated MA harvesting system.....	69
Table 6.7: Delay summary for skidder 1 from MA model simulation of Tigercat harvesting system with landing storage set at 15 tons	70
Table 6.8: Delay summary for skidder 2 from MA model simulation of Tigercat harvesting system with landing storage set at 15 tons	70
Table 6.9: Delay summary for skidder 1 from MA model simulation of Tigercat harvesting system with landing storage set at 100 tons	71
Table 6.10: Delay summary for skidder 2 from MA model simulation of Tigercat harvesting system with landing storage set at 100 tons	71
Table 6.11: MA model productivity output for Whole-tree harvesting system.....	73
Table 6.12: MA model productivity output for Cut-to-Length system	73
Table 6.13: MA model productivity output for hybrid system.....	73
Table 6.14: Unit cost comparison between MA model output and Hartsough et al. (1997)	74
Table 6.15: Standardized cost per unit comparison between MA model and Hartsough et al. (1997) for three harvesting systems.	75
Table 7.1: Default parameter input values used for example simulations of HSA model:	77
Table 7.2: Default cost input values for example simulations of HSA model.	78
Table 7.3: Input parameter values for example simulation of thinning of a pine plantation on undulating terrain.....	89
Table 7.4: Harvest system productivity rates for practical application of HSA model example simulation	90
Table 7.5: Initial distance of fellers from the landing.....	94
Table 7.6: Initialize time for skidders (seconds).....	94
Table 7.7: Productivity of machines in Step 1 (initial system machine allocation combination)	96
Table 7.8: Utilization of machines in Step 1 (initial system machine allocation combination)	96

Table 7.9: Production potentials of machines in Step 1 (initial machine allocation combination)	97
Table 7.10: Estimated effect of removing a skidder in Step 2.....	97
Table 7.11: Estimated effect of adding a processor in Step 2.....	98
Table 7.12: Productivity of machines in Step 2.....	99
Table 7.13: Utilization of machines in Step 2	99
Table 7.14: Production potentials for machines in Step 2	100
Table 7.15: Effect of removing a skidder in Step 3	100
Table 7.16: Effect of adding a processor in Step 3	101
Table 7.17: Productivity of machines in Step 3.....	101
Table 7.18: Utilization of machines in Step 3	102
Table 7.19: Production potential of machines in Step 3	102
Table 7.20: Add a feller in Step 4	103
Table 7.21: Effect of removing a skidder in Step 4	103
Table 7.22: Effect of adding a processor in Step 4	104
Table 7.23: Productivity of machines in Step 4.....	105
Table 7.24: Utilization of machines in Step 4	105
Table 7.25: Production potential of machines in Step 4	106
Table 7.26: Effect of adding a feller in Step 5.....	106
Table 7.27: Effect of removing a skidder in Step 5	107
Table 7.28: Effect of adding a processor in Step 5.....	107
Table 7.29: Effect of removing a processor in Step 5.....	108
Table 7.30: Machine allocation options in Step 5.....	108
Table 7.31: Productivity of machines in Step 5.....	109
Table 7.32: Utilization of machines in Step 5	109
Table 7.33: Production potential of machines in Step 5	110
Table 7.34: Effect of adding a feller in Step 6.....	110
Table 7.35: Effect of removing a skidder in Step 6	111
Table 7.36: Effect of adding a processor in Step 6	111
Table 7.37: Effect of removing a processor in Step 6.....	112
Table 7.38: Machine allocation options in Step 6.....	112
Table 7.39: Productivity of machines in Step 6.....	113
Table 7.40: Utilization of machines in Step 6	113
Table 7.41: Production potential of machines in Step 6	113
Table 7.42: Add feller in Step 7.....	114
Table 7.43: Remove skidder in Step 7	115
Table 7.44: Add processor in Step 7	115
Table 7.45: Remove processor in Step 7	116
Table 7.46: Productivity of machines in Step 7	116
Table 7.47: Utilization of machines in Step 7	117
Table 7.48: Initial machine allocation for machine substitution system 1	118
Table 7.49: Alternative machine allocation for machine substitution system 1	118
Table 7.50: Initial machine allocation for machine substitution system 2	119
Table 7.51: Final machine allocation for machine substitution system 2.....	120
Table 7.52: Initial machine allocation for machine substitution system 3	120
Table 7.53: Final machine allocation for machine substitution system 3.....	120

Table 7.54: Machine allocation for skidder assignment method evaluation	121
Table 7.55: Example logger's harvesting machines to be allocated	123
Table 7.56: Mechanized harvesting system machine allocation.....	124
Table 7.57: Manual harvesting system machine allocation	124

CHAPTER 1. INTRODUCTION

In the current business environment in the southeastern United States, timber-harvesting contractors typically operate high-cost harvesting systems on a narrow profit margin. An average contractor may have \$1.5million invested in machinery and operating costs of around \$500 per hour. With such a large investment loggers must manage their systems efficiently to ensure profitability (Rodgers 2002).

Although loggers are independent businesses, a recent survey showed that they typically contract for one consuming organization or wood dealer, with many of their tracts being assigned by this organization. The survey also showed that the typical system assignment methodology was on a first-come-first-served basis. Mismatching of systems to stands was estimated to be a significant problem for 40 percent of logging contractors (Rodgers 2002).

To economically justify the high capital investment in a forest harvesting business, the system must maintain high capacity utilization. The equipment combination is a key factor in determining the success of a forest harvesting system (Corwin *et al.* 1988). Many harvesting systems are designed for flexibility so that they can operate with relative effectiveness on a range of site, stand and system conditions. This flexibility to operate on a wide range of conditions may result in inefficiency on any specific tract (pers. comm. Rodgers 2002).

Two harvest system issues that are important to the logging industry in the southeast United States:

1. Harvest system assignment
2. Harvest system machine management

Harvest system assignment is important because different systems are inherently more suited to particular sites and stands than other systems. The purpose of this approach is to evaluate whether the best system is assigned to a stand. Much production capacity can be lost through assigning systems on an uninformed basis. Failing to take

into account the system potential on a particular site when making the assignment decision can cause a system to perform poorly, resulting in production losses.

Harvest system machine management is important because loggers must maximize capacity utilization to be as competitive as possible in the business environment in which they operate. This means they must identify imbalance within the system and mitigate this inefficiency by tailoring organization of the machines allocated to the system to achieve the best possible combination and the most efficient production. The challenge that must be met is to improve technical knowledge of forest harvesting systems so as to identify bottlenecks within the system. One method for identifying bottlenecks is to incorporate real-time information technology to measure the output of each harvesting system component. It is important that real-time information technology is incorporated in an informed fashion so that only critical information is collected to control the costs of installing and managing the technology, and the avoid overloading users with non-critical information that is not necessary to management; this harvest system model will attempt to facilitate possible approaches.

1.1 Objectives

Predicting the performance of harvesting systems is a difficult task. The machines themselves are very complex and are working in a constantly changing environment where they interact with other machines and are influenced by a range of site and stand factors (Gingras 1988). While the potential of an individual machine can be quantified through production studies, the effect on productivity from a variable environment and interactions with other machinery are, more difficult to gauge (Gingras 1989). This research will capture expert knowledge from literature and industry professionals, and employ this knowledge in a way that can be used operationally to improve the design and management of harvesting systems.

STELLA systems dynamics simulation software will be used to provide a platform for the solution to the issues of system assignment and machine management. STELLA has been applied effectively in the solution of log truck scheduling in the Log

Truck Simulation System model (Barrett 2001). STELLA will be used to develop two forest harvesting system models:

1. A computer-based analysis tool to evaluate the impact of system assignment decisions on system productivity and efficiency, as well as the impacts of key site and timber-stand characteristics on system productivity and efficiency.
2. A computer-based analysis tool to evaluate machine allocation decisions with respect to system and machine productivity and efficiency.

Model 1 deals with the assignment of harvesting systems and as such is designated as the Harvest System Assignment model. This model will allow users to evaluate the productivity of a particular harvesting system subject to constraints that are imposed as a result of system assignment.

Model 2 has a focus on the system design. It will allow machines to be allocated to a system to evaluate the value of each allocation combination. This model will be called the Machine Allocation model. It will allow users to evaluate the potential of a particular system combination and manage machine assignment. A key assumption to the Machine Allocation model is that the assignment decisions are made for a large pool of machinery that can be assigned to any one of multiple harvesting sites. This model will provide feedback to further research on system and machine management, and the potential for incorporation of real-time information technology.

CHAPTER 2. LITERATURE REVIEW

2.1. Existing Forest Harvesting Models

Computer simulation of logging systems began in the late 1960s. The goal of most logging system simulations has been to determine productivity, costs and the effect of changes to the system on productivity and costs (Goulet, Iff and Sirois, 1979). The following is a synopsis of many previous and existing forest harvesting models in chronological order.

2.1.1. Georgia Tech Model (1968)

This model is a General Purpose Simulation Software (GPSS) simulation of the production of 5'3" pulpwood. The model requires 19 variables and 15 distribution parameters to describe the system. The output is a GPSS summary with average performance values (Goulet *et al.* 1979).

2.1.2. Auburn Pulpwood Harvesting System Simulator (1969)

This model is based in FORTRAN and is a time-oriented simulation of southeastern pulpwood operations. It consists of two phases – production and transportation. The production phase includes: felling, delimbing and topping, skidding, bucking, bunching and loading. The transportation phase is simply the movement of trucks between the landing and mill (Goulet *et al.* 1979)

This model is composed of components – groups of like operations. Each component is assigned to a particular harvesting function and interactions among components are modeled using buffer inventories. A uniform time increment is used, and component cycle times must be evenly divisible by the uniform time increment for the model to run (Goulet *et al.* 1979).

The systems modeled are eight shortwood and six tree-length harvesting configurations. The output of the model is in the form of three reports: end of hour, end of day and end of week. End of day and end of week reports include a cost per log and production rates (Hool *et al.* 1972, Goulet *et al.* 1979).

All times used as inputs to the model are average cycle times that reflect the occurrence of variation due to delays. The model is deterministic in nature but can be modified to incorporate non-deterministic features using the Monte Carlo or other simulation techniques (Hool *et al.* 1972, Goulet *et al.* 1979).

2.1.3. Timber harvesting model for Appalachia (1973)

This model was one of the early attempts to provide a flexible productivity and cost estimator that could simulate a range of harvesting systems from cable skidders to cable yarders. All felling was assumed to be with a chainsaw (Biller and Johnson 1973).

Production study data was used to develop production functions for the model and generic cost information was used in cost calculation per unit of production and time. The output included information about distribution of time in elemental activities for general system components. The model included the capability to change the system to gauge the effect of possible changes on productivity and cost (Biller and Johnson 1973).

2.1.4. Simulation Applied to Logging Systems – SAPLOS (1973)

SAPLOS is a general logging simulation model, which is based in FORTRAN/GASP IV (Goulet *et al.* 1979; Goulet *et al.* 1980). It identifies five typical points where bottlenecks occur in a logging operation: stump, skid road, landing, prehaul deck and processing point. The activities that deliver logs to each point are modeled by identifying equipment and end-of-service events at each point. The model can simulate a very wide range of logging systems from small pulpwood crews to cable yarding crews (Goulet *et al.* 1979; Goulet *et al.* 1980).

Inputs to this model consist of cost and system configuration data and two subroutines. The first subroutine represents tree characteristics such as volume and

height. The second subroutine represents stand conditions such as slope and stocking. The output gives estimates of average production and cost, with specific production and cost statements for each activity and the system as a whole (Goulet *et al.* 1979; Goulet *et al.* 1980).

2.1.5. Appalachian Logging Simulator (1973)

This model was developed with the goal of improving the logging system. It models different system configurations and reports productivity averages. Average productivities are used to determine where imbalance may lay and the magnitude of the productivity imbalance. The user has the capacity to change the number of each type of machine in the system. Costs are reported using the machine rate methodology (Martin 1973).

2.1.6. Forest Harvesting Simulation Model – FHSM (1975)

FHSM is a FORTRAN/GASP II timber and pulpwood-harvesting simulator. It consists of modules for: felling, limbing, bucking and limbing, bucking at the stump, skidding, bucking at the landing, loading, hauling and unloading. Modules can be selected and combined to tailor the model to a specific system. Interactions among modules are modeled with wood inventories and equipment operating capacities. The operational times of modules are created using elemental operating times for the operations. There is no inclusion of stochastic delays in the model (Goulet *et al.* 1979; Goulet *et al.* 1980).

Inputs to the model are standard cruise data, and frequency distributions from time and motion studies. This makes the model stochastic; the user controls the level of detail. The output from the model is in the form of a single report containing production and processing time by machine and total wood volume delivered to mill. There is no economic analysis included (Goulet *et al.* 1979; Goulet *et al.* 1980).

2.1.7. Timber Harvesting and Transportation Simulator – THATS (1975)

THATS is a FORTRAN based model that simulates standard harvesting configurations. It consists of felling-limbing-topping, bunching, skidding, bucking, loading, and hauling. There is also a road construction component (Goulet *et al.* 1979; Goulet *et al.* 1980).

Inputs to this simulation include: cost, stand data, average and standard deviations for the operation being modeled. The averages and standard deviations are used to generate events within the model. Random variable event times are assumed to be normally distributed; a logarithmic function is applied to the distribution when the time-study data shows a skewing (Goulet *et al.* 1979; Goulet *et al.* 1980).

Wood flow through the system is modeled by volume. The input to the operation is a tree and the output is a volume. An in-process inventory exists between operations. The output of the model is a basic table from which the user constructs the performance variables of interest. There is also a cost accounting component (Goulet *et al.* 1979; Goulet *et al.* 1980).

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

FCTS consists of a chipping model and a transport model both are built in GPSS. The model simulates feller-bunchers, skidders, a chipper and trucks in the field, and the trucks at the mill (Goulet *et al.* 1979; Goulet *et al.* 1980).

This is one of the earlier graphical simulation models where the Cartesian coordinates and volume of every tree in the stand must be specified. Tree identity is maintained until it has been chipped. The skidder movements are modeled such that spatial location of each skidder is known at all times and they can move around one another (Goulet *et al.* 1979; Goulet *et al.* 1980).

The feller-buncher and skidder types can also be specified to describe machine characteristics, so that a specific machine can be simulated in the system. The output of the model is a production and cost summary for each machine and an energy consumption estimate (Goulet *et al.* 1979; Goulet *et al.* 1980).

2.1.9. Harvesting System Simulator – HSS (1976)

HSS is a FORTRAN based simulation of a harvesting system. The user specified system configuration contains a maximum of 14 machines divided into 6 aggregations of similar machines (Goulet *et al.* 1979; Goulet *et al.* 1980; Reisinger *et al.* 1986).

Differences in stand types, volume per acre, species composition, skidding distance and terrain can be modeled by dividing the tract into a maximum of 14 blocks. There is no constraint on the acreage or volume that each block can cover. A production rate is specified for each harvesting block and machine combination (Goulet *et al.* 1979; Goulet *et al.* 1980; Reisinger *et al.* 1986).

Non-productive periods can be modeled at specified times or applied stochastically. Repairs to machines that suffer from a breakdown can be made at the site of breakdown, by bringing the machine to the landing or hauling the machine to the shop. There are two types of delay; a minor delay leaves the machine in place while a major delay brings the machine back to the landing (Goulet *et al.* 1979; Goulet *et al.* 1980; Reisinger *et al.* 1986).

There are up to 27 variable/parameter inputs to the model, all or some of which can be used for a given run. The data used for inputs can be empirical, averages or theoretical distributions (Goulet *et al.* 1979; Goulet *et al.* 1980; Reisinger *et al.* 1986).

The output of the model is very detailed and includes time, production, cost and revenue. The reports tabulate this information by machine, phase and system on a weekly basis (Reisinger *et al.* 1986). Discounted cashflow and return on investment analyses can be made (Goulet *et al.* 1979; Goulet *et al.* 1980).

2.1.10. Residues for Power – REPO (1976)

This model was generated to simulate the specific process of transferring chipped harvesting residues to a power plant. Though it was developed for another purpose it can be applied more generally to materials handling to simulate a timber harvesting and transportation system (Goulet *et al.* 1979).

It is based in SIMCOMP and uses a fixed-time increment. Combinations of skidding, loading, transporting, unloading, sorting and shipping machines can be modeled. Flow of materials between operations is controlled by rate functions and materials-in-process inventories are used to show influence of one process on another (Goulet *et al.* 1979).

2.1.11. Harvesting Analysis Technique – HAT (1981)

This model began development in 1967. The simulator has three components: stand generator, machine simulator and harvesting system simulator (Stuart 1981).

This simulation is geared towards loblolly pine plantations and the actual HAT is a combined form of three models. The stand is defined using the *Pinus taeda* (PTAEDA) model. Individual trees are identified by their Cartesian location and have an associated physical description of size in the model. The generalized machine simulator (GENMAC) is included in the program set to model harvesting machine activities. The Harvesting System Simulator (HSS) is used to simulate harvesting systems which can be composed of up to 14 machines (Stuart 1981).

The HAT is used by first generating a stand using the PTAEDA model. The GENMAC model is run to generate a simulation summary report for each machine, a BUNDLE file describing the form and location of felled trees, PRODUCTION AND OPERATIONS file containing production distributions and a RESIDUAL file describing the remaining stand, if any. The PRODUCTION AND OPERATIONS file from GENMAC is used as input to the HSS model (Stuart 1981).

2.1.12. Program For Logging Cost Estimation – PROLOG (1982)

PROLOG is a menu driven cost analysis program, similar to LCAP (section 2.2.15), but based in FORTRAN. It was initially developed for students and consists of five sections to describe the system: general assumptions, equipment descriptions, labor wage information, reporting options and file management (Reisinger *et al.* 1986).

Inputs to the first three sections consist of information about working time, fixed and variable costs and average production rates of the system and specifically for each machine. The last two sections are used to detail what output from the program the user wants and how that will be arranged (Reisinger *et al.* 1986).

2.1.13. Geometric Modeling Of Thinning System Performance (1983)

This model was developed to model mechanized thinning to characterize the productivity and costs of thinning. It is applied in evaluating existing, proposed and conceptual aspects of feller-buncher design (Fridley and Jorgensen 1983).

Elemental equations are used to generate cycle times and are functional upon the characteristics of the feller-buncher and key site and stand parameters (Fridley and Jorgensen 1983).

2.1.14. Model for predicting logging machine productivity (1983)

This is a numerical model designed to provide estimates of productivity, and variation in productivity for existing and developing machine concepts. The model calculates volume produced and elemental production times. It returns the average and variance of the production and time (Meng 1983).

2.1.15. Logging Cost Analysis Package – LCAP (1984)

This is a Beginners All-purpose Symbolic Instruction Code (BASIC) menu driven program for calculating logging costs. It consists of four sections: machinery costs, labor costs, miscellaneous costs and summary table. Cost calculations are based on machine rate (Reisinger *et al.* 1986).

Inputs are costs and rates entered by the user for each of the required data. Output is given by hour, day, month and year, for each of the three cost sections and summarized in the summary table section (Reisinger *et al.* 1986).

2.1.16. Auburn Harvesting Analyzer – AHA (1985)

AHA is a spreadsheet used to analyze the performance of different allocations of logging systems to tracts. The spreadsheet template is divided into four sections: stocking, general tract information, machine productivity and machine cost. Templates are available for mechanized tree length, chainsaw felling, cable skidders, and forwarders (Reisinger *et al.* 1986).

Inputs to the AHA are average values. The data is combined with regression equations to estimate productivity. Outputs are in the form of estimated numbers for productivity and costs, on a scheduled machine hour basis for machines and the system (Reisinger *et al.* 1986).

2.1.17. Harvesting System Analyzer – HSA (1985)

The HSA was developed in PASCAL, and consists of two menu driven programs and is designed for productivity and cost analysis of harvesting systems (Reisinger *et al.* 1986).

The first program describes each machine used in the system. Each machine is selected from one of 16 categories, selection of a machine produces default productivity variables and data can be specified for operating and fixed costs (Reisinger *et al.* 1986).

The second program estimates the time and cost for a specified harvesting system to log a tract of timber. It uses three variables, which describe the harvesting system, the machines in the harvesting system and the tract. The user enters tract data, which along with outputs from the first program, are used as inputs to the second program (Reisinger *et al.* 1986).

The output is given in two reports, the system report is in terms of the system, each function and each machine, and the tract report summarizes the tract characteristics. Productivity is given in volume of timber produced, and costs are per volume produced (Reisinger *et al.* 1986).

2.1.18. Interactive Simulator for Studying the Design of Feller-Bunchers (1985)

This model is an interactive simulation of a feller-buncher for evaluating the design of feller-bunchers, operational parameters such as thinning prescription and their effect on felling productivity performance (Fridley *et al.* 1985).

The simulation uses graphical animation to facilitate user interaction with the system. The user guides the movement and felling activities of the simulated machine. The simulation has five main components (Fridley *et al.* 1985):

1. stand data file
2. machine model description
3. path description
4. computer simulation program
5. graphical animation

Output is provided as trees cut per productive machine hour. This output can be used to gauge production potential for the machine and the effect of machine design parameters such as boom length on the overall harvesting performance of the machine (Fridley *et al.* 1985).

2.1.19. Tree Harvesting Simulator – TREESIM (1986)

TREESIM is a spreadsheet-based analyzer that estimates system productivity and costs. Inputs to TREESIM include basic productivity, cost, stand and overhead data (Dremann 1986).

Output is displayed in tables, which are viewed by selecting them from a menu. Results can be calculated for costs and revenues, system productivity, trucking requirements and skidding requirements for a given production rate (Dremann 1986).

2.1.20. Operator Variability In Interactive Feller-Buncher Simulation (1987)

This model uses graphical animation to assist users in making activity selection in the interactive harvest simulation (Greene *et al.* 1987).

The stand is generated with piece size and stocking parameters, there are no site parameters. The output is a summary of operator performance including distance traveled, average times and productivity (Greene *et al.* 1987).

The model has been used to compare the effect of utilization with productivity and to examine any learning curve effect (Greene *et al.* 1987).

2.1.21. Discrete State, Continuous Parameter Markov Process Harvesting System Analysis (1988)

This model examines the interaction between a grapple skidder and a mechanical slasher. It uses analysis of machine states to determine productivity and efficiency (Hassler *et al.* 1988).

The input to the system is pre-felled bunches that are assumed to have been felled by a feller buncher. The skidder transports bunches to the slasher which cross-cuts the stems. Interactions are controlled with a production buffer which is the accumulation of un-cut stems waiting for the slasher. Processing times are fitted to either Erlang or mixed Erlang distributions (Hassler *et al.* 1988).

2.1.22. Animated Mechanized Tree Feller Interactive Simulator (1990)

This model is an interactive simulation geared to providing feedback about design of mechanical feller-bunchers. The output can be used to study the success of the felling-bunching operation of feller-bunchers and be used as input for skidding and forwarding studies. The purpose of the model is to infer improvements to the design and operation of feller bunchers (Block and Fridley 1990).

2.1.23. Timber Harvesting Analyses and Design Using Simulation (1990)

This model is a tree-to-mill simulation of logging systems. It uses a network based simulation method, the user can tailor the simulation to a specific system. It incorporates up to 13 harvesting processes, however the model is flexible enough that harvesting processes can be combined if performed by a single machine (Randhawa and Olsen 1990).

The inputs to the model are the harvest size, material flow sequence through the harvest system, distribution of sizes for trees, logs and pulpwood. Also, buffer inventories between processes, number of each type of machine performing each process, machine parameters and delay distributions (Randhawa and Olsen 1990).

The simulation output outlines the processing times, utilization of machinery, delay summaries, material flow distributions and costs per unit of production and time (Randhawa and Olsen 1990).

This model analyzes the performance of harvesting systems and allows the user to make defined modifications to the system to support the goal of system improvement (Randhawa and Olsen 1990).

2.1.24. Ground Based Harvesting System Simulation – GB-SIM (1993)

GB-SIM is a FORTRAN approach to simulation of stump to truck production from conventional ground-based harvesting systems in Appalachian hardwood stands. GB-SIM stochastically simulates production based on inputs of stand information including unique piece identity and Cartesian coordinate location of pieces, harvest area dimensions. Control variables include maximum turn volumes and trees per turn for skidding and maximum inventory of felled trees. It also has the capability for the analyst to simulate partial cuts and clearcuts (Baumgras *et al.* 1993).

The output from the GB-SIM model provides a detailed description of production cycle attributes for each harvesting system component. It also includes cost and revenue

estimation capabilities. The principal focus of GB-SIM is to estimate timber harvesting cost and revenue trends as a function of stand attributes (Baumgras *et al.* 1993).

2.1.25. Harvester-Forwarder Softwood Thinning Simulation (1995)

This model is a Promodel PC simulation of the activities and interactions of a harvester and forwarder logging system combination (Aedo-Ortiz *et al.* 1997).

Material flow through the system involves entities: trees at the head of the system, that become logs, which make up forwarder loads. The final output of the model is logs. The model is composed of four elements: felling and processing time, logs per tree, forwarder traveling empty, and forwarder loading and traveling. Inputs are diameter at breast height, distance traveled out and number of stops to accumulate a load (Aedo-Ortiz *et al.* 1997).

Output is productivity per hour. This simulation has the capability to estimate production variation per hour based on average extraction distance over the course of time taking advantage of the stochastic nature of the simulation. This feature provides significant insight into the system production function (Aedo-Ortiz *et al.* 1997).

2.1.26. Stand, Harvest, and Equipment Interactions (1998)

This simulation models harvesting systems graphically to simulate the interaction between machinery and the effect of various stand parameters and harvest intensity on productivity (Wang *et al.* 1998).

Inputs to the model are the stand conditions, harvest method and machines. The simulation models felling and extraction patterns (Wang *et al.* 1998).

Output is summary information about individual machine productivity, travel distances and production times. An important analysis component of this model is travel intensity to estimate site impacts from various machine combinations and extraction patterns (Wang *et al.* 1998).

2.1.27. Simulation of a Single-Grip Harvester (1999)

This simulation was developed to evaluate different silvicultural treatments and compare different machine concepts (Eliasson 1999).

The model is structured into two parts: machine movement and boom-processing cycle. Elemental times are calculated based upon generated stand parameters and user-specified machine specifications. The output from the model tabulates absolute and percentage time consumption relative to the silvicultural treatment and machine specifications (Eliasson 1999).

2.1.28. Bundle Distribution and Skidder Assignment (2001)

This model is a simulation of the skidding and loading activities of a tree length logging system. It models the effect of skid distance on skidder productivity, and the interaction between skidders and loaders. The model is developed in the AnyLogic 4.0 software and additional functionality can be incorporated using Java (McDonald *et al.* 2001).

The model allows the user to compare the effect of skidding assignment pattern on the productivity of the skidder and the associated interactions between the skidder and the loader. No consideration was given to terrain, obstacles or interactions among skidders away from the landing (McDonald *et al.* 2001).

2.2. Types of Forest Harvesting Models

2.2.1. Scope

The scope of existing forest harvesting models can be grouped into four categories:

1. Single machine (Eliasson and Lageson 1999; Eliasson 1998; Greene *et al.* 1987; Block and Fridley 1990; Wang *et al.* 1998; Bragg *et al.* 1994)
2. Multiple machines/in-woods system (Randhawa and Olsen 1990, McDonald *et al.* 2001; Aedo-Ortiz *et al.* 1997; Wang and Greene 1999)
3. Transportation system (Barret 2001; Feng and Douglas 1993; McCormack 1990; Shen and Sessions 1989)
4. Tree-to-Mill systems (Randhawa and Olsen 1990; Goulet *et al.* 1980; Dremann 1986).

Single machine models are very involved simulations of the activity of a machine and the interaction of a machine with site and stand parameters. These simulations are used to examine the activity of a single machine in detail especially for the design of operational improvements (Eliasson 1998, Eliasson and Lageson 1999, Greene *et al.* 1987, Block and Fridley 1990, Wang *et al.* 1998, Bragg *et al.* 1994).

Multiple machines/In-woods System models typically lose some of the detail in the simulation of the individual machines, however the general complexity of the model increases when the issue of machine interactions is introduced. Typically, the machine interactions are dealt with by using buffer inventories. When a buffer inventory reaches its maximum level, the activity feeding that inventory enters a blockage delay state. If a machine exhausts a buffer inventory it enters a delay state through starvation (Randhawa and Olsen 1990, McDonald *et al.* 2001; Aedo-Ortiz *et al.* 1997; Wang and Greene 1999). The only treatment of congestion dealt with in models is in single-machine models where boomed felling machines are restricted by standing stems (Greene *et al.* 1987, Eliasson 1998, Fridley and Jorgensen 1983). There is no effective treatment of machine interactions away from inventories.

The complexity of truck transportation systems has been captured in computer simulation models (Barrett 2001). Trucking is oftentimes a pivotal aspect of harvest

system effectiveness (Barret 2001; Feng and Douglas 1993; McCormack 1990; Shen and Sessions 1989) so cannot be excluded altogether from consideration in the development of harvesting analysis models. A deterministic approach to truck scheduling for harvest system models can capture impacts of trucking without interfering with the harvesting model.

Tree to mill harvesting models have the most comprehensive scope for harvesting system modeling. This approach recognizes the importance of all aspects of the supply chain from the woods to the consumer (Randhawa and Olsen 1990; Goulet *et al.* 1980; Dremann 1986). Given the uncertainty that still exists in modeling the harvesting system, but not the trucking system, this scope is too broad to be applied in this research.

The first goal of this research project is to develop a flexible harvest system model which can be used to support harvest system assignment decisions. The scope of the model is defined in the goal in that it must address a complete in-woods harvesting system. However, the complexity of examining individual machinery in such a model will result in a large number of inputs being required, causing the model to be very user-intensive to run. For the purposes of education of loggers and managers, a less intensive level of interaction to drive the model is desired. The treatment of the system and the simulation method will be definitive factors in the description of this model.

The second goal of this research project is to develop a machine management model which will allow users to design a better harvesting system. This task can be better defined using the literature review covered so far. The conceptual structure of this model will be similar to that employed in the more recent models such as the models by Aedo-Ortiz *et al.* (1995), Baumgras *et al.* (1993), Wang *et al.* (1998) and Eliasson (1999). It will identify individual machines, the activities of each machine and explicitly deal with interactions among the machines. The nature of the STELLA software dictates that the resulting model will not display the same discrete object-oriented content as these models, but will rather be more continuously behavior-oriented.

2.2.2. Simulation Method

The forest harvesting models outlined previously encompass a range of simulation methods. These range from the very simplest spreadsheet calculation analysis, to very complex interactive graphics simulations. The simulation method used depends on three key factors:

1. Technology available
2. Scope of the model
3. Type of analysis desired from the model

The earlier models presented date from the late 1960s and early 1970s. Computer hardware and software technology was at this time much less developed than in the 1980s and especially the 1990s. Similarly, the field of harvesting system analysis was not as important because the technology employed in the harvesting systems at the time was much less complex than it is today.

The simplest harvesting models are the deterministic models: AHA (Reisinger *et al.* 1986), LCAP (Reisinger *et al.* 1986), TREESIM (Dremann 1986), and APHSS (Goulet *et al.* 1979). These can predict the average performance of a system but do not reflect the variability that is inherent with any logging system. These models are adequate to perform the analyses they were designed for. However, the analyses of harvesting systems appropriate for the industrial climate of today require a much more intensive investigation of the system. It is important to provide a model that is flexible enough to capture the range of harvesting systems that are used while still maintaining a sophisticated analysis of the system. Deterministic models are not suited for such application.

Development beyond deterministic models began with some of the earliest models which began to employ stochastic processes in the simulation. This type of simulation includes most of the forest harvesting system models described previously. THATS (Goulet *et al.* 1979, Goulet *et al.* 1980) and GB-SIM (Baumgras *et al.* 1993) are good examples of application of this type of simulation. Stochastic features are integral to all recent models and are necessary because of the variability in operating conditions and productivity that is inherent in all harvesting systems. The variability in harvesting

systems must be reflected in a harvesting system model if it is to provide an effective analysis of a system.

Stochastic variation is a key feature that must be incorporated to meet the harvest system assignment model goal for this research. Variability in terms of the site, stand and system parameters to which the system is subject must be reflected in the output from the simulation so that the user understands the importance of not only the mean values but the variation about the mean. The incorporation of stochastic variability is a key feature that the STELLA software can model effectively and will be integral in the development of a harvest system assignment model.

Deeper levels of modeling complexity such as interactivity and user interaction methods such as graphical simulation are useful for some aspects of harvest system analysis. The detail required to develop models with these features has meant that applications to date (Wang et al. 1999, Greene et al. 1985) have been single machine models and used for studying machines rather than systems. Graphical simulation has potential in harvesting system simulation to convey to the user relativity among machinery, especially where issues such as congestion are addressed. User-interaction is more applicable to single machine models because of the intensity of interaction required to run the simulation. STELLA software does not have the capability to apply graphical simulation in forest harvesting system models. However, spatial location can be implied conceptually by utilizing scalar variables which convey magnitude and can in combination imply location relative to an origin such as the landing. This complexity may be necessary to develop machine interactions to the desired level, especially if congestion among machinery is to be examined.

CHAPTER 3. STELLA® SOFTWARE

Systems dynamics is the study of dynamic systems through the modeling of a series of cause-and-effect relationships with feedbacks. This field was developed in the late 1950s by Jay W. Forrester and has been applied to business, industrial, natural and social processes (Forrester 1961, High Performance Systems, Inc 2001).

The software used to create the forest harvesting system models in this research is STELLA 7.0 systems dynamics simulation software. STELLA is a code generating language that removes the modeler from much of the complexity of computer language programming. The modeler interacts with a modeling interface with a selection of generic modeling entities:

- Stocks
- Flows
- Converters
- Connectors
- Decision Process Diamonds

Stocks are accumulations of material. The material can be anything designated by the user such as harvested timber. Stocks can also be used more conceptually to measure time, by using inflows and outflows to a stock, it can be utilized in a manner similar to a stopwatch to measure elemental times for forest harvesting machines. Stocks enable incorporation of discrete concepts in an otherwise continuous modeling environment. Material is accumulated into and removed from stocks using flows (High Performance Systems, Inc 1997).

Flows allow the movement of material into and out of stocks. Flows do not have to connect to stocks but can be independent and used as a measure of movement of material in a purely continuous environment. The flow rate can be controlled independently or be influenced by external elements such as other flows, stocks or converters.

Converters are conceptual tools that can be inputs to the model, calculations, graphical functions or statistical distributions. Converters are generally continuous but

can act discretely by using PULSE or STEP functions. A relationship between a converter and a flow or another converter is shown through the use of a connector.

A connector simply shows the relationship of one entity with another. Connectors are directional showing which entity is the independent variable and which is the dependent variable.

The decision process diamond is an entity that is a recent addition to STELLA software and it is first incorporated on Version 7.0. The purpose of the decision process diamond is to simplify the structure of a model. It creates a sub-model layer which is hidden but can be viewed by drilling down into the model logic.

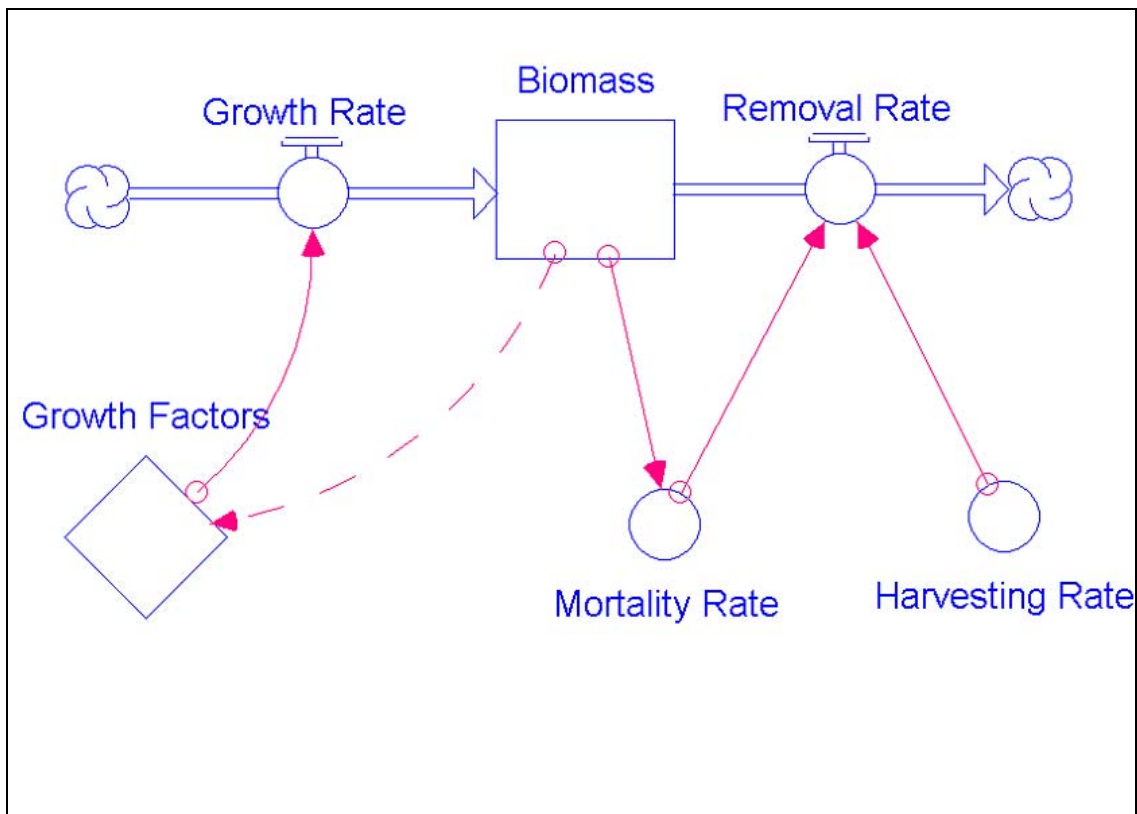


Figure 3.1: Example use of STELLA model layer entities

Figure 3.1 illustrates a simple application of STELLA to the complex problem of mixed age class stand management. "Biomass" is a stock representing all vegetation in the stand. The amount of "Biomass" is controlled by the accumulations from the flow "Growth Rate" and removals from the flow "Removal Rate". The magnitude of the flow "Growth Rate" is controlled by the decision process diamond "Growth Factors", this

influence is represented by the connector between the two entities. The decision process diamond incorporates feedback from the stock “Biomass” which affects such growth factors as the light intensity in the understory and available soil moisture. For simplicity these growth factors have been grouped into the “Growth Factors” decision process diamond which reduces the number of entities on the model layer making it much easier to understand. The magnitude of the flow “Removals” is controlled by two factors. The first is the converter “Mortality Rate” which is controlled in turn by the stock “Biomass”. The implication is that as the biomass in the stand increases so too does the mortality rate by way of competition. The second converter is “Harvesting Rate” which is an input by the model user and is independent of all other entities in the model. The “Harvesting Rate” is controlled by the user and can either be fixed or varied during the simulation so that the “Harvesting Rate” is not so high as to deplete the “Biomass” of the stand.

The purpose of this example is to evaluate the effect of “Harvesting Rate” on the stand “Biomass” over time. The harvesting rate will affect the “Removal Rate” thus reducing the “Biomass.” As the “Biomass” is reduced the “Growth Factors” are affected resulting in a change in the “Growth Rate.” What is of interest is how different values of “Harvesting Rate” affect the “Biomass” and “Growth Rate.” A low “Harvesting Rate” will probably cause a small decrease in “Biomass” and a small increase in “Growth Rate.” At some point as the “Harvest Rate” increases the “Removals Rate” will be greater than the “Growth Rate,” resulting in a long term decrease in “Biomass.” By changing “Harvesting Rate” and observing trends in the “Growth Rate” and “Biomass” the user can reach conclusions about the long-term sustainable “Harvest Rate” and the effect of deviating from this rate.

CHAPTER 4. HARVEST SYSTEM

ASSIGNMENT (HSA) MODEL

4.1. Objective

The goal of the HSA model is to develop an analysis tool to support harvesting manager and logger decision-making for tract purchase and system assignment.

4.2. Scope

To accomplish the goal for the HSA model, a computer-based model will be developed to analyze typical ground-based harvesting systems as they occur in the southeast United States. The analysis will be subject to key site, stand and system parameters as identified from literature and expert opinion.

The goal for this model is to develop an analysis tool to support system assignment decision-making. As such, the issue of facilitating system improvement is beyond the scope of this project. With this rationale, the harvesting system will be treated conceptually as a “black box” in this model. The “black box” concept means that individual components of the harvesting system will not be distinguished. Rather the system will be examined as a single entity. Through intensive literature research, parameterized production functions that represent the performance and limitations of the system, as a whole, can be determined. This approach will meet the goal for this model because it will produce outputs describing the performance of the logging system subject to relevant site, stand and system parameters. The key to making this approach effective is to utilize the software in a manner that allows the system definition to be as descriptive as possible while still maintaining flexibility in the model.

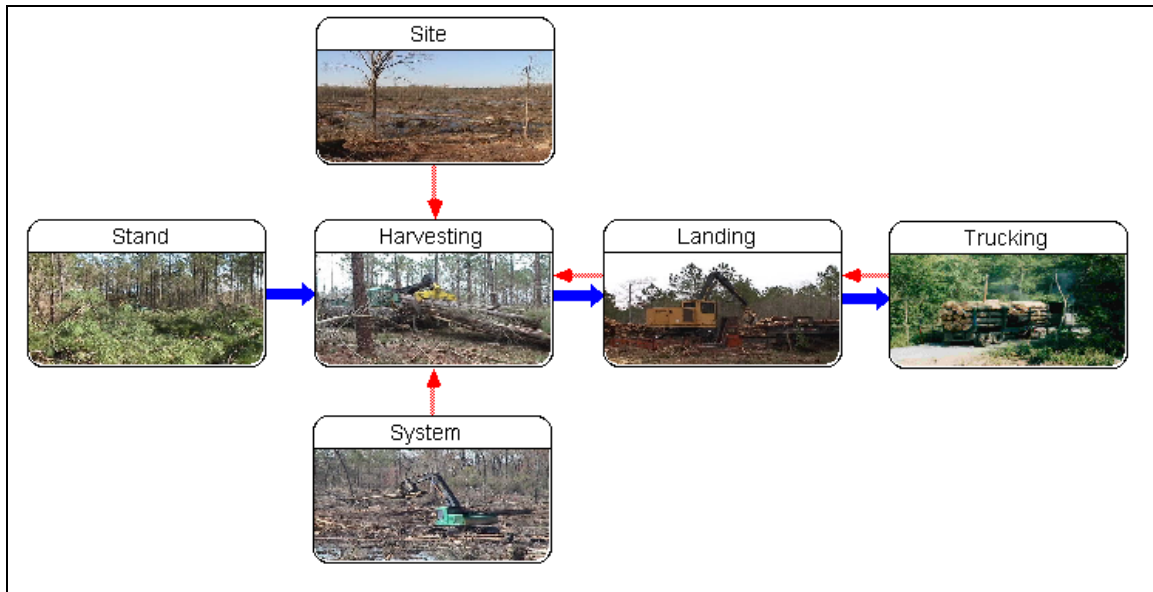


Figure 4.1: Harvesting system scope.

Small red arrows represent feedback and interdependencies in the model. Heavy blue arrows describe where material movement occurs.

Figure 4.1 illustrates the scope and treatment of the harvesting system by the HSA model and further defines how the “black box” concept is applied. The harvesting system is not defined explicitly, rather it is inferred by defining its production potential and limitations to that potential. When interacting with the model the user defines the site and stand parameters to describe characteristics of the terrain and tract. Further system constraints are also defined which include the system inputs, the landing and trucking characteristics.

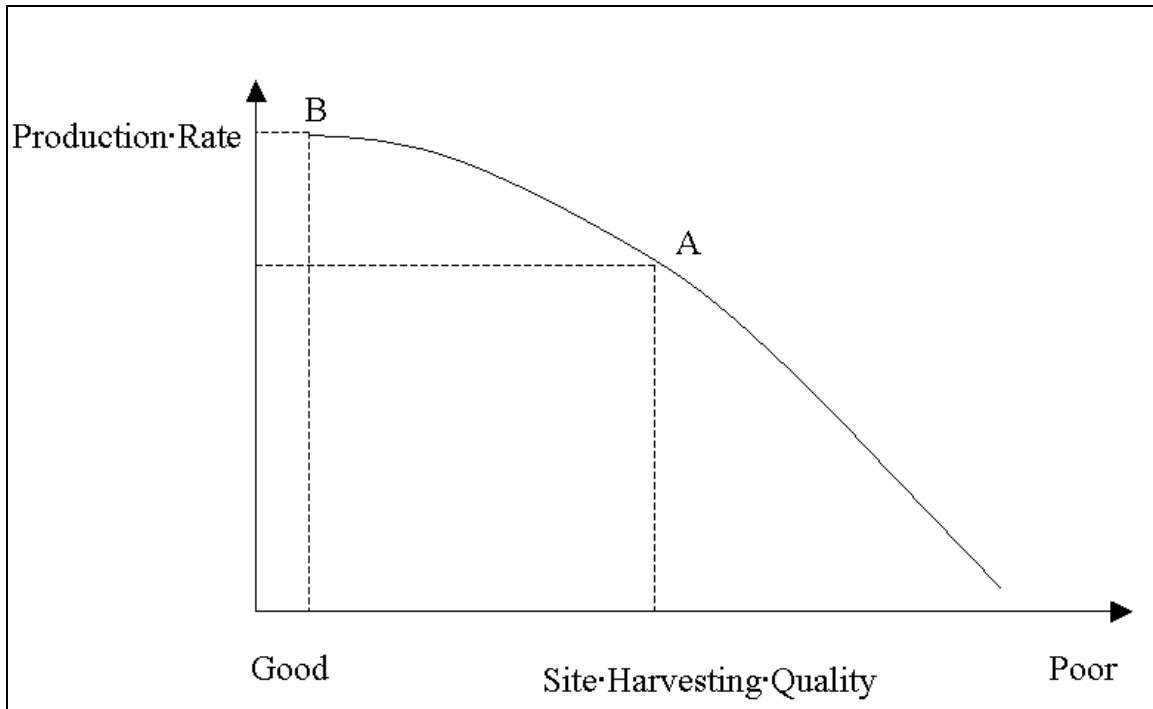


Figure 4.2: Production function for a system

Figure 4.2 illustrates how the HSA model approaches the assignment decision support problem. The maximum system productivity potential that can be obtained by a particular system when; site, stand and system parameters are not limiting, is represented by point B. However, through assignment inefficiencies a system may be assigned to a non-optimal site such as represented by point A. As a result of being assigned to a non-optimal site, the production rate associated with a system is less than that which could be obtained on an optimal site. The goal of the HSA model is to quantify site quality effects on production. It can be used to place systems on sites where the deviation of the actual system assignment productivity (A) from the optimal system assignment productivity (B) is minimized.

To accurately describe production functions for different types of systems four, common general types of ground-based forest harvesting system were defined (Sloan 2001) and incorporated in the model:

1. Manual chainsaw felling and cable skidding
2. Mechanical felling and grapple skidding
3. Shovel bunching and grapple skidding
4. Cut-to-Length harvesting and forwarding

4.2.1. Manual chainsaw felling and cable skidding system

The manual system is a flexible system which is common in mountainous areas of the southeast. The harvesting process involves manual felling, delimbing and topping by a chainsaw operator. Bucking can occur either before skidding at the stump or subsequent to skidding on the landing. Skidding of the felled trees is performed using a rubber-tired skidder equipped with a spooled wire cable and chokers. The skidder operator manually manipulates the wire cable out to the felled trees and secures the trees with the chokers. The trees are then winched up to the skidder and dragged to the landing for further processing by either chainsaw operators or a knuckle-boom loader equipped with a hydraulic saw buck. Logs are stacked on the landing by the loader and loaded onto trucks for delivery to consumers.

The advantages of this system are that it is flexible and can operate on a wide variety of terrain conditions, especially steeper slopes which limit movement of machinery. This system type also copes well with natural stands which may have large and variable trees, and many product sorts.

The disadvantages of a manual harvesting crew are that it is relatively labor intensive, and that because there are one or more workers on the ground operating chainsaws this type of system is inherently more dangerous, than systems using mechanical felling, topping and delimbing.

4.2.2. Mechanized felling and grapple skidding system

The mechanized system is typically a high production system. Felling is performed mechanically using wheeled or tracked feller-buncher machines. Typically, felled trees are bunched into piles to facilitate acquisition (building of a turn for extraction) by the grapple skidder. The skidder transports felled trees to the landing and processing at or near the landing may involve either a delimbing gate, manual chainsaw delimbing or mechanized processing with a stroke delimeter or loader operated saw buck.

This type of system typically operates on terrain that is negotiable by wheeled machinery. Mechanized systems are very efficient in plantation harvest applications where the terrain is flat to rolling and the tree size is uniform.

Mechanized systems are relatively high production systems, especially where the conditions are relatively uniform such as in a plantation harvests. This type of system is most often limited by terrain conditions such as steep slopes and wet ground conditions.

4.2.3. Shovel bunching and grapple skidding system

There are two general variations of this type of system. The first is in swamp harvests where the shovel machine is used to create a skid road of felled trees and then forwards machine felled trees from the stump to the skid roads for the grapple skidders to extract. The second type of shovel system is in mountainous terrain where mechanized or manually chainsaw felled timber is forwarded and bunched to facilitate extraction with a grapple skidder.

The advantages of the shovel system are flexibility in adverse site conditions and the productivity advantages inherent with mechanization in harvesting systems. The disadvantages of shovel systems are high limitations in partial cuts and investment in extra machinery is required which increases the owning and operating costs that must be defrayed through increased production.

4.2.4. Cut-to-Length harvesting and forwarding system

The cut-to-length system is a highly mechanized system involving specialized machinery. Typically the harvester fells and processes trees into log lengths. The log lengths are bunched as they are cut. Subsequently the forwarder travels through the harvested site and uses an integral loader to accumulate a load in a bunk. The load in the forwarder bunk is fully suspended above the ground. The forwarder then transports the load to the landing or roadside and loads directly onto truck road trailers or stockpiles the wood for subsequent truck transportation to the consumer.

The advantages of the cut-to-length system are relatively lower site impacts, safe working environment, ability to deal with small trees and steep terrain conditions. The disadvantages of the cut-to-length system are that it has a relatively low production rate given the high capital investment necessary to form such a system.

4.3. Structure

Literature yielded productivity information for each general type of system, or machines used in each, to describe the productivity functions for each type of system relative to key site, stand and system parameters. The productivity information was collected based on the four system types to define individual productivity curves that are characteristic of how each system performs. The purpose is to model the performance of each system with a level of precision that will represent characteristic performance capabilities of the different systems.

The productivity functions were built from available information. While the available information for mechanized and cut-to-length systems was very complete, the information on manual systems was more limited, and production functions for the shovel system non-existent. There was enough information for manual systems to produce a satisfactory set of production functions.

The set of production functions for the shovel system were approximated based upon assumptions:

1. The machines used in a shovel system are the same as in a mechanized system (with exception of the shovel machine), therefore the shovel system has production functions identical to the mechanized system for site and stand parameters
2. The nature of a shovel system, especially the shovel machine, is such that it requires open areas to maneuver the logs (pers. comm. Shaffer 2002) so it is much more limited than a mechanized system in partial cuts.

To maintain flexibility in the system, productivity is calculated down, rather than up. A single set of production functions are used to determine productivity, regardless of the magnitude. The user can compare similar systems with different machine combinations to evaluate the effect of scale, without having to redefine the set of production functions.

Each type of system is assumed to have a production potential frontier. The maximum production potential for a particular system is its production rate when all site, stand and system parameters are within optimal ranges and the only limitations on the production rate are the capacity of the machinery and the operator experience. Parameters are dealt with using individually parameterized production function equations which determine the effect on production potential based upon deviation of a parameter value from the optimal range. When one or more parameters are non-optimal there is a negative effect on productivity. The effect on productivity is calculated proportionately to enable one production function to apply to a continuous range of production potential values for a system type. The negative proportional effect on productivity that is generated is applied to the production potential of the system generating an instantaneous productivity. This calculation method is applied for each iteration of the model and as site, stand and system parameters vary over time the effect of this variation is reflected in the productivity of the system.

The calculation method applied in the HSA model relies on generalized production functions that approximate how a system would likely be affected. The productivity calculation process is simple in nature and can be approximated using

expected values from the input distributions. The inputs used are relatively simple to incorporate, however, combined with the simple calculation process the output is very generalized and may be difficult to apply to a particular system. Also, interactions among parameters are not dealt with in detail. The affect of interactions can be observed in the output however, the capacity to control the magnitude of interactions is imprecise and performed implicitly.

The output from the HSA model provides a widely applicable approximation of production tendency for four general system types over a range of site, stand and system parameter values.

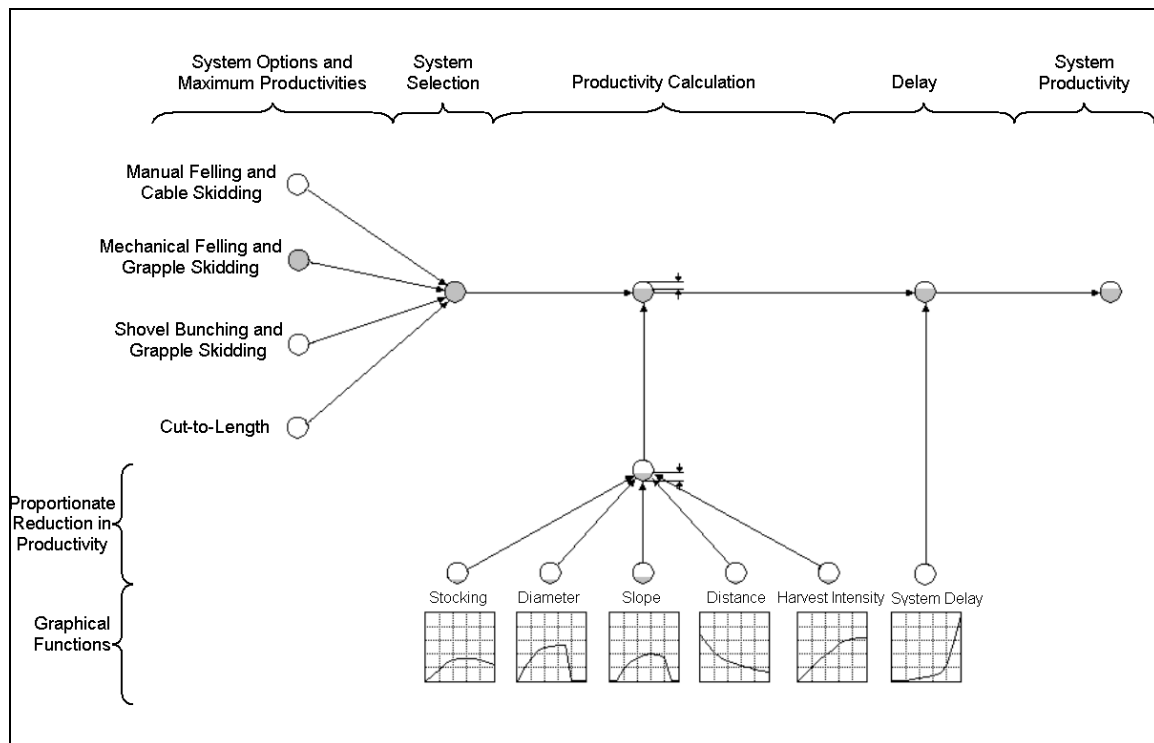


Figure 4.3: Schematic Diagram of HSA model showing system selection, productivity calculations and delay function

Figure 4.3 explicitly illustrates the productivity calculation process for the HSA model. One of the four general system types is selected - in this instance a “mechanical felling and grapple skidding” system. Associated with the system type is a maximum production potential which can be specified by the user. The production potential for the

system of interest is then input into the model. The user specifies the distribution of each of the site, stand and system parameters.

The HSA simulation runs a series of iterations representing time increments. At the completion of each time increment the model runs an iteration to determine how the simulation behaved during that time period. Parameter values are generated stochastically and the effect of each of the parameters is calculated from the associated distributions. The combined effect of the parameters on the productivity of the system is calculated and applied to the system, thus generating a productivity which is reported for that iteration. The productivity calculation method occurs provided that the system is not in a delayed state.

4.4. Inputs

There are three types of input parameters to the HSA Model:

- Site
- Stand
- System

The site and stand parameters represent terrain and tract characteristics which constrain productivity of harvesting systems.

The site parameters of most importance are:

- Site slope: slope influences the ability of machinery to move about the site. With increasing slope machines become more limited through having to change their pattern and rate of movement to minimize the loss of traction and the possibility of rollover (Andersson 1997, Gingras 1989, Hartsough *et al.* 1997, Richardson 1989).
- Skid (or forward) distance: Skid distance influences the rate at which felled trees and logs are delivered to the landing. At increasing skid distance the time taken to deliver a load to the landing increases (Andersson 1992, Hassler *et al.* 2000, Klepac and Rummer 2000, Andersson 1994, Richardson 1994).
- Harvest Intensity: The proportion of basal area to be removed in the harvest. Harvest intensity influences the amount of movement required to harvest timber. With decreasing harvest intensity the distance between harvest trees increases and

the number standing trees remaining as obstacles increases (Eliasson 2000, Greene *et al.* 1987, Lageson 1997, Winsauer *et al.* 1984, Andersson 1994).

The stand parameters of most importance are:

- Piece Size: the size of the trees influences the rate of volume removal at which the stand is harvested. With increasing piece size the harvesting rate increases (up to a maximum piece size) because of marginal increases in the gain in volume for each tree harvested versus the time to harvest each tree (Andersson 1992, Andersson 1997, Araki 1992, Araki 1994, Gingras 1989, Greene *et al.* 1987, Hartsough *et al.* 1997, Lanford and Stokes 1996, McConchie and Evanson 1995, Richardson 1989, Winsauer *et al.* 1984, Andersson 1994, Richardson 1994)
- Stand stocking: stand stocking influences the amount of machinery movement per unit of volume harvested. With decreasing stocking more movement is required between trees which increases the amount of time to harvest each tree (Andersson 1997, Araki 1992, Eliasson 2000, Greene *et al.* 1987, Hassler *et al.* 2000, Richardson 1989, Winsauer *et al.* 1984, Richardson 1994)
- Stand size: stand size does not influence site-harvesting productivity. Rather stand size influences overall productivity by increasing effective time. As stand size increases the system spends a greater proportion of time harvesting and a less time moving between harvest tracts.

System parameters determined to be of importance:

- Landing storage capacity: landing storage capacity is the amount of logs that can be stored on the landing. When landing capacity is reached, no more logs can be stored on the landing and so the harvesting system must wait until space becomes available.
- Trucking capacity: trucking capacity is a function of the interval between trucks arriving at the landing and the amount of logs that can be removed from the landing by each truck. Trucking capacity in this model influences the amount of logs that can be removed from the landing per unit of time.

- System delays: system delays are non-productive time that result from scheduled and unscheduled work stoppages such as equipment breakdowns, rest breaks, weather stoppages, injuries, and machine maintenance and repair.

4.4.1. Cost inputs

The purpose of including costs in the analysis is to provide a metric for comparison that is meaningful to users, and, which takes into account the size of investment thus providing a measure of scale.

Cost inputs are treated using generic harvest system hourly cost structures. Owning and operating costs are included as hourly rates. Owning costs are deemed as fixed costs and occur every hour when the system is scheduled to operate. Operating costs are deemed variable costs and occur during time when the system is actually operating.

A further level of cost structure is added by including a setup cost input. The reason for the inclusion of a setup cost is to include a measure of the cost of moves between tracts incurred by the harvesting system. For smaller tracts the move costs will be incurred more often. Because the move or setup cost is incurred with every move it must be defrayed with every tract to financially reach or pass the break-even point on a harvest and thus adds to the harvesting cost.

The information should be used for comparison purposes only and may not accurately reflect the actual costs for a specific operation.

4.4.2. Input Assumptions

- The stand parameters, piece size and stocking, and the site parameter slope are assumed to be normally distributed. These parameters are incorporated in the HSA model by defining the mean, standard deviation and range for each parameter.

- Skid distance is uniformly distributed. Skid distance is incorporated in the HSA model by defining the maximum skid distance and is calculated through a linear skidding pattern. The skidding starts near the landing and works away from the landing as the simulation progresses.

4.5. Productivity calculation

The productivity calculation in the HSA model occurs in a continuous manner as dictated by the continuous nature of the STELLA software.

If not in a delay state, the model will generate values for the site and stand parameters from the user-specified distributions. These values produce individual effects on productivity for each parameter which are combined and applied to the productivity potential to generate an instantaneous productivity.

4.6. Delays

4.6.1. System delays

System delays are designed to represent non-productive time that occurs because of events such as machine breakdowns, equipment failures, worker rest breaks, worker injuries and inclement weather.

Little research is available which describes the frequency and duration of such delays. Available research presents machine and system availability and utilization, there is no analytical dissemination of the causes of these inefficiencies. The available research lists the occurrence of delays but does not define the cause, the duration and frequency (Andersson 1992, Andersson 1994, Araki 1994, Meek 1993, Peterson 1987, Richardson 1989, Andersson 1997).

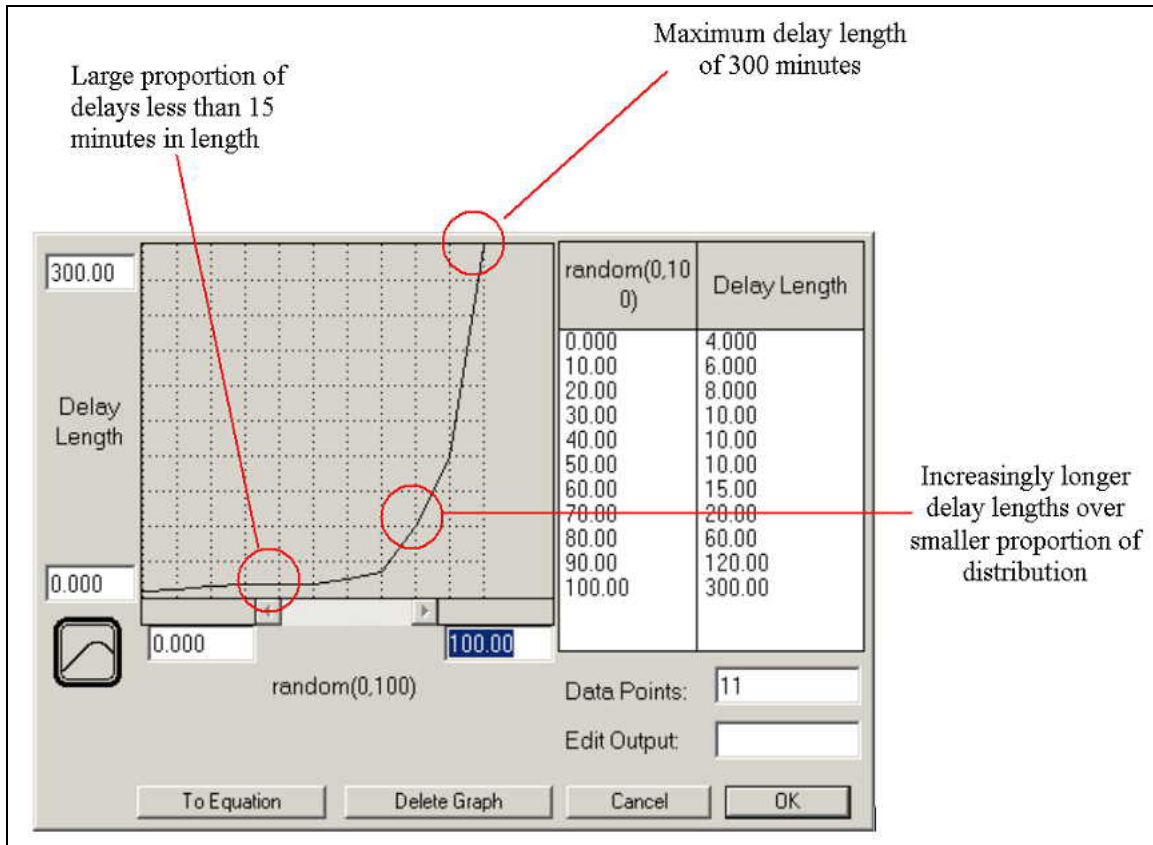


Figure 4.4: Example HSA model delay length function in the Stella programming environment

Professional opinion and research data points to delay distributions being typically J-shaped (pers. comm. Visser 2002). Figure 4.4 illustrates a delay distribution from the HSA model. In Figure 4.4, 60 percent of the delay lengths are less than 15 minutes, beyond this delay lengths increase up to a maximum delay length of 300 minutes. Delays are generated randomly subject to a Monte Carlo process at an hourly rate specified by the user. When a delay is generated the system enters a delay state and the delay length is calculated using a delay length function similar to Figure 4.4. After the delay length has expired the system enters a productive state again.

The expected value of a delay from Figure 4.4 is 51.2 minutes. To achieve a utilization of at least 80 percent given this expected delay length, a delay frequency of no more than 0.293 delays per hour is necessary (or one delay every 3.4 hours).

4.6.2. Landing storage delays

Landing storage delays are incorporated in this analysis for two reasons. The landing is an important control point in the supply chain.

In the scope of this research, the harvest system of interest ends at the landing. However, the ability of the harvest system to operate can be constrained by blockages when the landing storage space is completely utilized. In this context the landing storage is an important part of the analysis. It is a measure of the balance between harvesting capacity and the scheduled trucking capacity.

4.7. Simulation length

The HSA model uses hours as units of time and has 60 iterations per hour, or one iteration per minute. This level of resolution is necessary to accurately capture the material flows and delay states. The total simulation length is 500 hours. This length of simulation time allows most simulated harvests to be completed before the end of the simulation. If a harvest cannot be completed in this amount of time, the system will likely have reached a steady state or be showing indications of its long-term tendency.

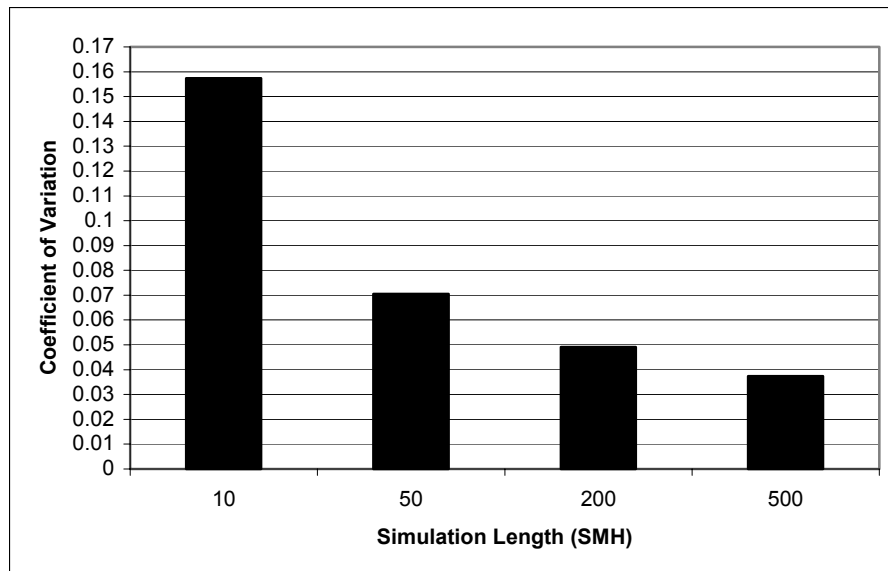


Figure 4.5: Coefficient of Variation at different simulation lengths for manual system with site, stand and system parameters set at default values. CV constructed from 10 runs at each level of simulation length.

The importance of choosing a long simulation length is illustrated in Figure 4.5 where the relative dispersal of the data points about the mean is shown using the Coefficient of Variation (CV) measure. A high CV will mean that several runs must be made of a simulation to obtain an accurately representative output, whereas a low CV will mean that only one run of a simulation must be made to obtain an accurately representative output. The benchmark CV decided upon for the HSA model was 0.05, any simulation length greater than 200 SMH would be acceptable (Figure 4.5). A simulation length of 500 SMH was chosen to provide greater accuracy and to allow enough time for most simulated harvests to be completed.

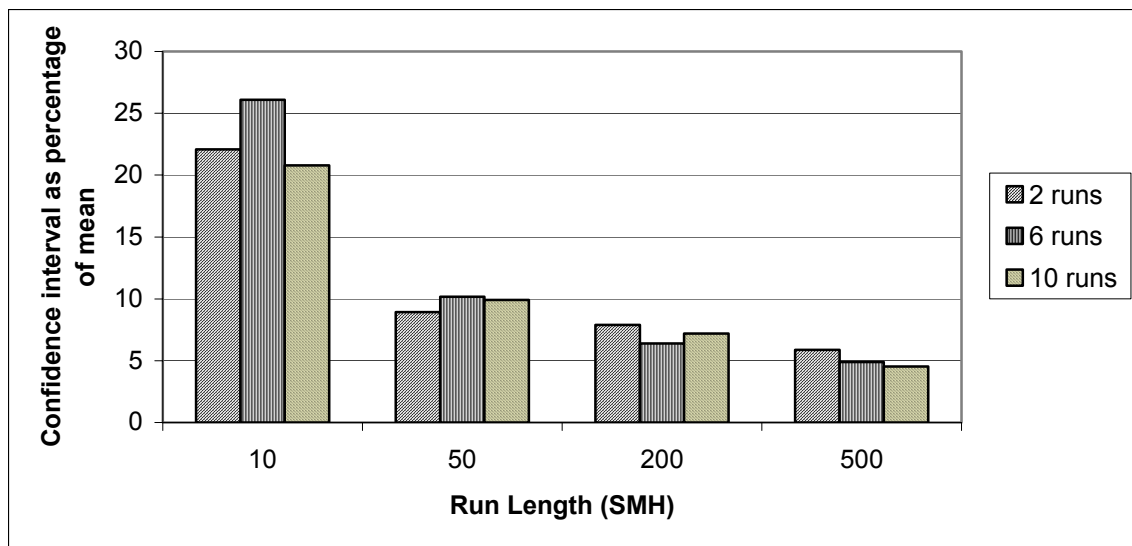


Figure 4.6: Comparison of the effect of run length and number of runs on the relative spread of the 95 percent confidence interval

There are two aspects to variability that are shown in Figure 4.6. The confidence interval is affected most by the run length; at longer run lengths the confidence interval is much narrower reflecting greater certainty in the results. For all numbers of runs at a run length of 500 SMH the confidence interval is narrower than any number of runs investigated at shorter run lengths.

The second aspect is the variation depending on the number of runs. The most accurate number of runs to perform at any level of run length varies. The number of runs

that is most appropriate depends on the run length that is being investigated. The narrowest confidence interval was obtained from ten runs at a run length of 500 SMH. The widest confidence interval was obtained from five runs at a run length of 10 SMH.

4.8. Outputs

To determine the effectiveness of the system three measures are appropriate:

1. Productivity
2. Efficiency
3. Unit cost

4.8.1. Productivity

The units of productivity measurement in the HSA model are tons of wood produced per hour. This measurement unit was chosen for its applicability to actual harvesting operations and the ease of conversion from tons to other units.

The purpose of measuring productivity is for performance evaluation and long-term planning. It is used to gauge the effectiveness of systems and to determine future courses of action (Brinkerhoff and Dressler 1990). For forest harvesting systems, typically paid per unit of production, the economic survival of the system is dependent on effective production.

4.8.2. Efficiency

Efficiency measurements in the HSA model are used to provide a comparison measure that can be used to compare different systems independently upon their relative effectiveness on a given site. The production efficiency is a measure of how close to the maximum point on a system production potential frontier a particular system is, on a given site. The measurement statistic is the production rate as a percentage of the maximum production potential for a particular system.

The cost efficiency is a measure of how close to the minimum point on the system cost potential frontier a particular system is on a given site. This can vary from the production efficiency depending on the costs associated with a system. This measure is included because it is a measure that relates the costs of production.

4.8.3. Cost calculation

There are three types of cost calculations in accordance with the three types of cost inputs used in the model. Fixed costs are incurred for every simulation hour over the course of the simulation until the harvest is complete, variable costs are incurred every simulation hour that the system is not in a delay state, and setup costs occur only at the start of the simulation. The total costs are not reported to the user. However, they can be readily calculated by multiplying the per ton cost by the total number of tons produced. Rather, the total costs are transformed into unit costs of time and production.

The unit costs of time are determined by dividing the cost by the total hours of time expended in the course of harvesting. This measurement returns the fixed, variable, setup and total cost per ton. The importance of this cost metric is that operating costs are usually determined per scheduled machine hour of harvest time. This rate is important for the logging contractor for system planning requirements and by including it, a relationship between system effectiveness and the hourly cost should be portrayed to the user.

Unit costs of production are determined by dividing the total cost by the total tons of production. This returns the fixed, variable, setup and total cost per ton. This cost metric is useful because logging rates are often specified by cost per ton so it is a generally accepted term in industry which has meaning to the people that this model is designed to serve. This cost metric also provides a standard for comparison. It allows a user to compare a system over different sites and determine the real effect on cost of production.

The HSA model is very powerful for system evaluation when using costs as an instrument of comparison. The HSA model provides cost output for the system at maximum production potential or optimal, as well as the cost output from the actual

simulation. This provides a benchmark for the system to provide perspective to the user on the system potential on the specified site.

The effectiveness of a system on a particular site is further disseminated through “costs of inefficiencies.” The costs of inefficiencies are designed to enlighten the user to the importance of each parameter in determining the effectiveness of the system and thus the cost per ton. The cost per ton was chosen as a metric for this output because it is a more meaningful cost figure to industry and represents real costs of production. The Cost of Inefficiency is calculated by parameter and based upon the proportionate contribution of each parameter to the difference in total cost per ton of the simulation from the optimal cost per ton. The Cost of Inefficiency is a powerful measure that illustrates in a meaningful manner the effectiveness of a particular system and directs the user to where gains are to be found by better system assignment.

CHAPTER 5. MACHINE ALLOCATION (MA) MODEL

5.1. Objective

The objective for the MA model is to develop a computer-based analysis tool to evaluate machine allocation decisions with respect to system and machine productivity and efficiency.

The primary focus of the MA model is to evaluate harvesting systems on a range of site and tract conditions, and develop machine allocation improvements. The second focus for the MA model is to facilitate the development of knowledge about system performance through identification of potential avenues for the incorporation of real-time information technology.

5.2. Scope

To accomplish the objective for this model the system definition must be very complete, the result is that structurally the system in the MA model is much more complicated than in the HSA model. Within the system, the activity of individual machinery and the flow of material between machines is integral to the success of this model.

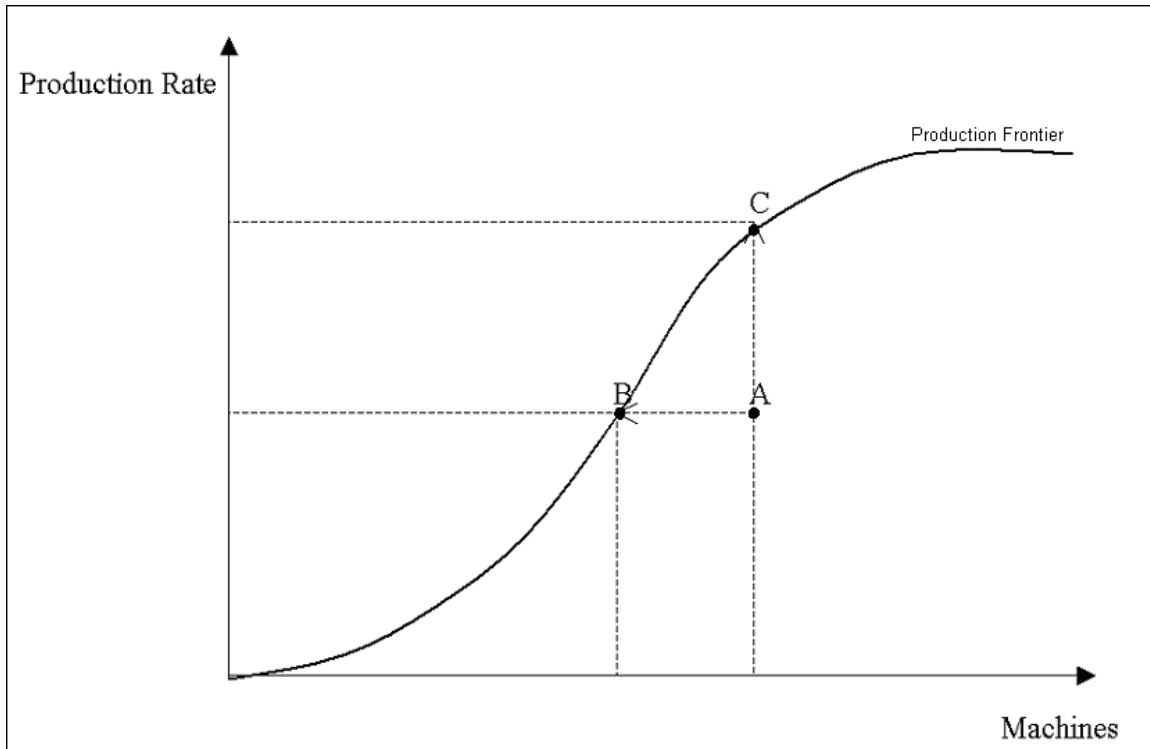


Figure 5.5.1: Production potential frontier for a harvesting system

Figure 5.1 illustrates a macroscopic view of conceptually how the MA model is used to improve harvesting systems to achieve better capacity utilization. Point A represents a real or theoretical point at which a certain combination of machines is producing a level of output. While the production potential frontier may not be known, by evaluating the system it can be deduced whether or not the system is near the frontier or away from the frontier as in Figure 5.1. The MA model offers the user the ability to deduce where the system is limited and make changes to the system in terms of the combination of machinery to move closer to the production potential frontier. For example, in Figure 5.1, a user may determine that skidding is limiting the production of the system. The user then swaps out a small skidder from the system and replaces it with a larger skidder and moves up to point C on the production potential frontier. Alternatively, if swapping to a larger skidder is not an option the user may elect to drop a feller from the system reducing both the production and the capital, thus moving the system to the production potential frontier at point B.

The MA model is used to determine how close to the production potential frontier a system is and courses of action to reduce this deviation thus maximizing capacity utilization.

The MA model incorporates machines from each type of system addressed in the discussion of scope for the HSA model. However, the system definitions are flexible because hybrid systems can be created by the user and evaluated as well as the fixed system definitions discussed already.

While the HSA model dealt with production for a fixed system, the MA model is concerned with determining the optimal point on the production function only. The MA model can evaluate the tendency of the system production function over a range of harvesting site qualities, however, this is beyond the scope of interest and can be best accomplished using the HSA model. While a combined system could potentially evaluate when changes to the system should be made as site, stand and system parameters vary, this complexity is beyond the scope of this research.

5.3. Structure

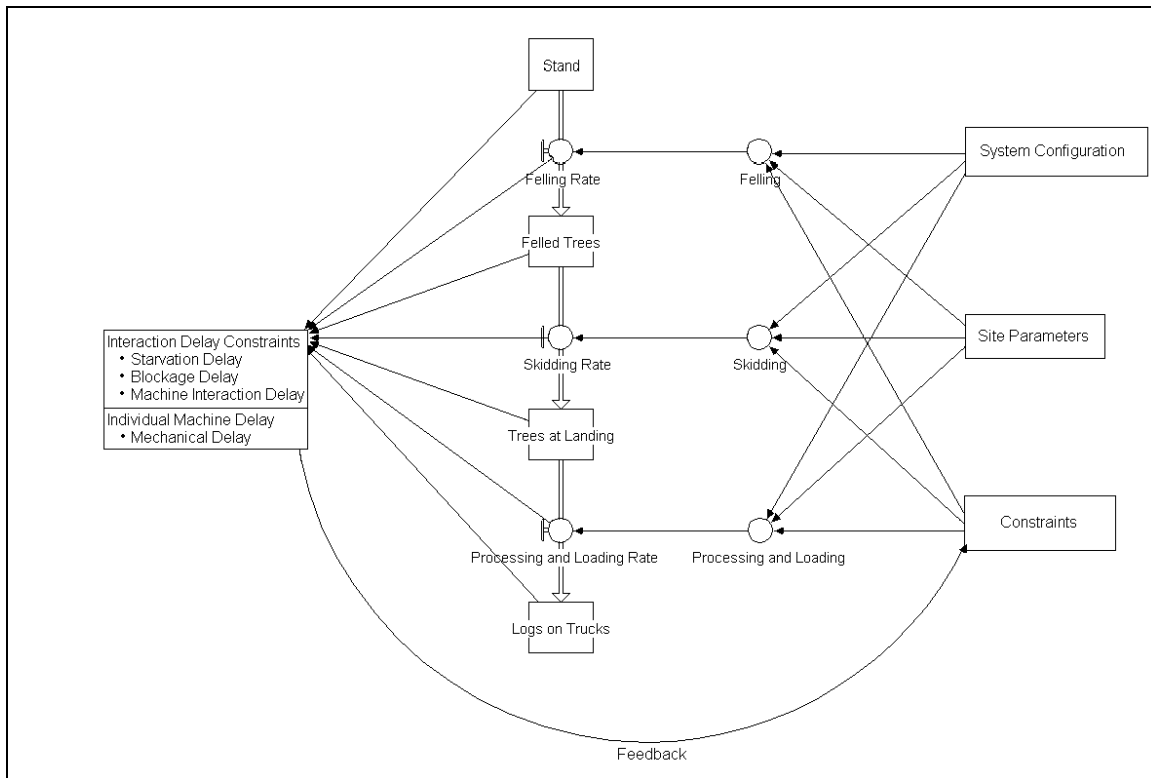


Figure 5.5.2: MA model schematic diagram

Figure 5.2 illustrates the conceptual relationships between the processes within a logging system and the associated controlling factors. By controlling the system configuration, constraints to the system such as bottlenecks and congestion can be alleviated, thus improving capacity utilization.

The model will be composed of an array of machine models that produce output based upon productivity formulas derived from literature. The operation of these machine models will be limited by bottlenecks in the system. By investigating the performance of each machine the bottlenecks can be identified and propositions made to mitigate the effect of the bottleneck on capacity utilization.

Timber inventories are a concept that is designed to provide a link between the model and the “real-world.” Timber is assigned to inventories, which represent accumulations of timber at key control points in the system. Machines draw timber from and deposit into inventories – all timber flows are accounted for. The inventories also represent conceptual machine locations to infer harvest layout and machine state.

5.4. Inputs

There are two types of inputs to the MA model.

1. System
2. General

System inputs define the composition of the harvesting system. This type of input describes the number and type of machines in the system, along with the way in which these machines interact. There are three categories of machines representing the three phases of harvesting that the MA model deals with: felling, skidding and processing. Within each of these general categories there are two or more general machine types. The machine types used in the MA model are listed in Table 5.1.

Table 5.5.1: Machine types. For each of the three phases of the harvesting operation incorporated in the MA model there are two or more machine types available.

Felling	Skidding	Processing
Feller-Buncher	Cable Skidder	Motor-Manual
Harvester	Grapple Skidder	Processor
Motor-Manual (Chainsaw)	Forwarder	

A complete harvesting system must include felling and skidding components. One system that consists of only felling and skidding is a cut-to-length system where processing is performed in conjunction with the felling phase. Another system consisting of only felling and skidding is a whole-tree system that extracts the unmerchantable volume along with merchantable material. Generally, a processing phase is integral to the specification of a complete harvesting system. When a processing component is included it can occur either prior to, or subsequent to, the skidding phase depending on the particular system that the user is modeling.

5.4.1. System inputs

System inputs describe the composition of the harvesting system of interest. The composition may, from the user's perspective, represent a real system, or any one of a large number of theoretical machine combinations. Up to three phases in the harvesting system can be modeled, and within each of the phases the user can include up to five machines from any of the machine types listed in Table 4.1. It is possible to have several different machine types in each phase in each system. The MA model is flexible enough to model a large range of machine allocation combinations, while maintaining specificity in the system definition.

5.4.2. General Inputs

General inputs to the MA model are site and stand parameters that influence operation of machinery. General inputs include:

- Piece size – key factor in determining the production rate of harvesting machines (Winsauer *et al.* 1984, Gingras 1988), especially machines for which the cycle is

devoted to only one or several trees as is the case for felling and processing machines. The marginal gains in volume per piece exceed the marginal increase in time taken to process each piece so that larger piece size results in higher productivity, up to the machine capacity limits (Gingras 1988)

- Stocking – the density of trees per acre. Stocking affects the number of trees that can be reached from a certain point and thus the amount of machine movement necessary. Stocking is especially important for felling machines, the effect of stocking on skidding and processing machines is generally not as important.
- Skid distance – the distance from the location of the felled trees/logs in the woods to the landing in feet. Skid distance is important only for skidding machines because it affects the time taken to move a load to the landing and return to acquire the next load (Andersson 1992, Greene and Stokes 1988, Klepac and Rummer 2000, Kluender et al. 1997, Richardson and Makkonen 1994, Tufts 1997). Skid distance is treated as a function of the felling machine when processing follows skidding (treated as a parameter of the processing machine when processing precedes skidding). Skid distance is specified using a starting distance, travel direction and travel pattern.

5.5. Simulation calculations

5.5.1. General input parameter calculation

- Piece size is calculated using a uniform random distribution formula from a user-specified range.
- Stocking is fixed to the value entered by the user.
- Skid distance is recalculated every time a skidder departs an inventory. The skidding pattern is assumed to follow the felling pattern. There are two felling patterns: away travel only (the feller travels away from the landing as it is felling, then returns to the landing before beginning the next felling phase), and away-

and-towards the landing travel (the feller fells as it is moving away and as it is moving towards the landing). The felling pattern is selected in the felling inputs screen. When a skidder departs an inventory, the skid distance changes by an amount determined by the skidder payload. When the skid distance reaches or passes the maximum skid distance, the skid distance will decrease. The maximum skid distance can be determined using an optimization technique described in Clark et al. (1997) that results in the best landing layout to minimize the skid distance for a particular number of landings. The away-from-landing travel direction begins when the skid distance to landing is less than 20 feet.

5.5.2. Skidder assignment

Skidder assignment is the decision of where to send a skidder to acquire a load. There are four skidder assignment methods employed in the MA model:

1. Fixed – A skidder is assigned to an inventory from which it draws exclusively for the entirety of the simulation.
2. Largest Inventory – Skidders are assigned to whichever is the largest felled inventory. This method is dynamic and the assignment sequence cannot be predicted.
3. Inventory Control – If the skidded inventory falls below a certain level skidders will travel to inventories which are closer, when the inventory is above that level, skidders will travel to inventories which are further away. The goal is to moderate the level of skidded inventory. This is another dynamic method and is used where processing occurs subsequent to skidding.
4. Sequence – Five, preset, inventories are scheduled for each skidder and the skidder assignment cycles through the list sequentially. The sequence method is a deterministic approach and is an expansion of the fixed assignment method.

5.5.3. Productivity Calculation

Machine productivity is determined using elemental or cycle time equations. A cycle is composed of one or more states. To complete a cycle a machine must move through each of the states. At the completion of the states in a cycle, a new cycle begins and the machine returns to the initial state. Skidding machines have four key cycle states – at landing, travel out, acquire load and travel in. Felling and processing machines have a single cycle state - there is no distinction between the move and production elements for these machines. Elemental equations determine residence time in cycle states for machines. When a machine has been in a state for the required residence time it moves to the next state or cycle. At the completion of a cycle, the machine is assumed to have produced output and an output flow is recorded.

Most machine types in the MA model have more than one set of underlying cycle time equations. The purpose is to mitigate bias that is intrinsic by the nature of productivity studies. Productivity studies are empirical studies conducted under unique conditions of site, stand, machines, operators and weather. To use a set of cycle time equations uniquely to represent a machine type without recognizing that there is inherent bias will result in spurious accuracy (pers. comm. Shaffer 2002). The MA model utilizes the arithmetic average of multiple elemental/cycle equations to define the cycles for each machine type. Utilizing multiple equations to define the elements/cycle for machine types mitigates some of the bias providing a more applicable output. The element/cycle time approach utilized in the MA model will not eliminate bias but the mitigating effect will improve confidence in the accuracy of the results. Bias will remain because of the small number of production functions used to define each machine, the amount of bias is reduced as more production functions are used to provide a more generally applicable central tendency.

Skidding machines have relatively long cycles by comparison to the felling and processing machines. Depending on the machine and the skid distance, the skid cycle times can range in excess of half an hour per turn. The elements of the skid cycle are of critical importance in the skidding cycle. For this reason, the four key elements of the skid cycle were determined from literature and are modeled in the MA model:

1. Travel out – unloaded movement of the skidding machine from the landing to a point in the woods where it begins acquiring a load.
2. Acquire load – movement of the machine and manipulation of the felled trees/logs into a secure manner for transport to the landing.
3. Travel in – loaded movement of the skidding machine from the acquisition point in the woods to the landing.
4. At landing – movement of the skidding machine and manipulation of felled trees/logs to deposit the load at the landing in a way that facilitates subsequent operations and the subsequent movement of the skidder.

The cycle times for felling and processing machine types are generally less than one minute in length. Considering the short cycle times, the importance of individual elements in the cycle and the type of information discerned from literature for these machine types, the total cycle is defined without the detail of cycle elements for these machine types.

At the completion of a machine cycle an output occurs. Felling and processing machines draw and produce output instantaneously at the completion of the cycle. Skidding machines, draw inventory at the completion of the acquisition state and deposit the inventory as output at the completion of the landing state. All flows of inventory are tracked and as such become the basis for productivity calculation. The total of all flows created by a machine, are weighed against the time elapsed to determine individual machine productivity. The machine capacity is determined empirically during the simulation. The maximum load size and minimum cycle time define the machine production capacity. The machine productivity is weighed against the machine production capacity to determine utilization.

5.5.4. Decision to Add/Remove Machines

The MA model evaluates the productivity and efficiency of all the machines in the system and provides an output of possible selections for machines to add to or remove from the system. From the possible selections provided by the MA model it also specifies

the “best” option. The best option is the possible machine addition (or removal) that results in the highest throughput per machine. The throughput per machine is used as a measure of efficiency because greater throughput per machine equates to higher capacity utilization – more production for the amount of investment.

Parameters:

i = an index for machine, $i = 1, 2, 3, 4, 5$

j = an index for phase (felling, skidding, processing), $i = 1, 2, 3$

q_{ij} = production potential (tons/SMH) of machine i in phase j

Decision Variables:

x_{ij} = 1 if machine i is used in phase j , 0 otherwise

n_j = number of machines in phase j

Y_{ij} = 1 if remove machine i from phase j , 0 otherwise

P_{ij} = productivity (tons per SMH) of machine i in phase j

U_{ij} = utilization (percent) of machine i in phase j

Q_{ij} = predicted system productivity from adding machine i to phase j

R_{ij} = predicted system productivity from removing machine i from phase j

C_{ij} = predicted system productivity from a change in the machine combination by adding/removing machine i to/from phase j

The number of machines in phase j is equal to the sum of machines used in phase j

$$n_j = \sum_{i=1}^5 x_{ij}, \forall j \quad (1)$$

The MA model makes suggestions as to the machine selection that will maximize throughput for any one change in the system machine allocation. It determines, given the combination of machinery now, which one machine can be added or removed to result in the largest throughput per machine.

The objective of making machine allocation changes is to maximize average throughput per machine:

$$Max \frac{\min \left(\sum_{i=1}^{n_1} P_{i1}, \sum_{i=1}^{n_2} P_{i2}, \sum_{i=1}^{n_3} P_{i3} \right)}{\sum_{j=1}^3 n_j} \quad (2)$$

The throughput of the system (controlled by the bottleneck), divided by the number of machines in the system determines the average system throughput per machine (Equation 2). We want to maximize the average system throughput per machine to maximize capacity utilization.

The general process is to determine which phases to add or remove machines and then within those phases, which machines to add or remove.

Decision to add machine:

Add machine if the addition of the extra machine will result in increased average throughput per machine. Increased average throughput is determined on a system phase basis. The production potential of the additional machine is added to the existing production rate for the system phase to which it is to be added. It is assumed that machines added to the system will have a utilization of 70 percent.

If a system phase is the bottleneck in a system and the addition of a machine will improve the productivity of that phase then a machine addition is suggested. A bottleneck has the highest average utilization of all phases.

If

$$\frac{\sum_{i=1}^{n_j} U_{ij}}{n_j} = \max \left(\frac{\sum_{i=1}^{n_1} U_{i1}}{n_1}, \frac{\sum_{i=1}^{n_2} U_{i2}}{n_2}, \frac{\sum_{i=1}^{n_3} U_{i3}}{n_3} \right) \quad (3)$$

and

$$\sum_{i=1}^{n_j} x_{ij} < 5$$

then addition of machine in phase j is possible.

If a particular phase (felling, skidding, processing) is the bottleneck in the system (has the highest utilization) (Equation 3), and there is a machine available to add to that phase then it could be added.

The following is the prediction of the productivity of the system when a machine is added to phase j :

Predicted productivity as a result of adding machine i to phase 1.

$$Q_{i1} = \min \left(\left(\sum_{i=1}^{n_1} P_{i1} + (q_{i1} * 0.7) \right), \sum_{i=1}^{n_2} P_{i2}, \sum_{i=1}^{n_3} P_{i3} \right) * (1 - x_{i1}) \quad (4)$$

The predicted productivity of the bottleneck phase in the system will be equal to the minimum of the predicted productivity in phase 1, the productivity in phase 2 or the productivity in phase 3. This equation is conditional upon the additional machine not already being in the system.

Predicted productivity as a result of adding machine i to phase 2.

$$Q_{i2} = \min \left(\sum_{i=1}^{n_1} P_{i1}, \left(\sum_{i=1}^{n_2} P_{i2} + (q_{i2} * 0.7) \right), \sum_{i=1}^{n_3} P_{i3} \right) * (1 - x_{i2}) \quad (5)$$

The predicted productivity of the bottleneck phase in the system will be equal to the minimum of the productivity in phase 1, the predicted productivity in phase 2 or the productivity in phase 3. This equation is conditional upon the additional machine not already being in the system.

Predicted productivity as a result of adding machine i to phase 3.

$$Q_{i3} = \min \left(\sum_{i=1}^{n_1} P_{i1}, \sum_{i=1}^{n_2} P_{i2}, \left(\sum_{i=1}^{n_3} P_{i3} + (q_{i3} * 0.7) \right) \right) * (1 - x_{i3}) \quad (6)$$

The predicted productivity of the bottleneck phase in the system will be equal to the minimum of the productivity in phase 1, the productivity in phase 2, or the predicted productivity in phase 3. This equation is conditional upon the additional machine not already being in the system.

Determination of estimated throughput per machine:

If

$$\frac{Q_{i1}}{\sum_{j=1}^3 n_j + 1} > \left(\frac{\min \left(\sum_{i=1}^{n_1} P_{i1}, \sum_{i=1}^{n_2} P_{i2}, \sum_{i=1}^{n_3} P_{i3} \right)}{\sum_{j=1}^3 n_j} \right) \quad (7)$$

Then the addition of a machine i in phase 1 will increase the average throughput per machine.

If

$$\frac{Q_{i2}}{\sum_{j=1}^3 n_j + 1} > \left(\frac{\min \left(\sum_{i=1}^{n_1} P_{i1}, \sum_{i=1}^{n_2} P_{i2}, \sum_{i=1}^{n_3} P_{i3} \right)}{\sum_{j=1}^3 n_j} \right) \quad (8)$$

Then the addition of a machine i in phase 2 will increase the average throughput per machine.

If

$$\frac{Q_{i3}}{\sum_{j=1}^3 n_j + 1} > \left(\frac{\min \left(\sum_{i=1}^{n_1} P_{i1}, \sum_{i=1}^{n_2} P_{i2}, \sum_{i=1}^{n_3} P_{i3} \right)}{\sum_{j=1}^3 n_j} \right) \quad (9)$$

Then the addition of a machine i in phase 3 will increase the average throughput per machine.

Decision to remove machine:

Remove machine, if removal of the machine will result in increased average throughput per machine. Machine removal is determined on a utilization basis.

$$\text{if } \frac{\sum_{i=1}^{n_j} U_{ij}}{n_j} \neq \max \left(\frac{\sum_{i=1}^{n_1} U_{i1}}{n_1}, \frac{\sum_{i=1}^{n_2} U_{i2}}{n_2}, \frac{\sum_{i=1}^{n_3} U_{i3}}{n_3} \right) \quad (10)$$

$$\text{and} \quad \sum_{i=1}^{n_j} x_{ij} \geq 2 \quad (11)$$

Then you can remove a machine from phase j

You can remove a machine from phase j , a non-bottleneck phase, identified as a phase that does not have the highest utilization of all phases (Equation 10), conditional on at least two machines existing in that phase (Equation 11) so that the productivity of the non-bottleneck phase will not become zero.

Remove machine from the non-bottleneck phase (determined in Equation 10, conditional on Equation 11), if the machine has the lowest utilization of all machines in that phase (Equation 12, 13, 14).

$$Y_{i1} = \begin{cases} 1 & \text{if } U_{i1} = \min_{k=1, \dots, 5} \{U_{k1}\}, \forall i \\ 0 & \text{otherwise} \end{cases} \quad (12)$$

$$Y_{i2} = \begin{cases} 1 & \text{if } U_{i2} = \min_{k=1, \dots, 5} \{U_{k2}\}, \forall i \\ 0 & \text{otherwise} \end{cases} \quad (13)$$

$$Y_{i3} = \begin{cases} 1 & \text{if } U_{i3} = \min_{k=1, \dots, 5} \{U_{k3}\}, \forall i \\ 0 & \text{otherwise} \end{cases} \quad (14)$$

The predicted productivity of the system after a machine removal (Equation 15, 16, 17) is the minimum of the current production rates, and the current production rate for the non-bottleneck phase less the production of the removed machine.

$$R_{i1} = \min \left(\left(\sum_{i=1}^{n_1} P_{i1} * (1 - Y_{i1}) \right), \sum_{i=1}^{n_2} P_{i2}, \sum_{i=1}^{n_3} P_{i3} \right) \quad (15)$$

$$R_{i2} = \min \left(\sum_{i=1}^{n_1} P_{i1}, \left(\sum_{i=1}^{n_2} P_{i2} * (1 - Y_{i2}) \right), \sum_{i=1}^{n_3} P_{i3} \right) \quad (16)$$

$$R_{i3} = \min \left(\sum_{i=1}^{n_1} P_{i1}, \sum_{i=1}^{n_2} P_{i2}, \left(\sum_{i=1}^{n_3} P_{i3} * (1 - Y_{i3}) \right) \right) \quad (17)$$

The determination of whether the machine removal will increase or decrease production is made using similar methodology to Equations 7, 8, 9. The estimated throughput per machine after the change is compared to the current throughput per machine before the change. If the estimated throughput per machine is greater than the current then the change is recommended.

Choose to add or remove machines in phase 1 based upon which will give the highest average throughput per machine.

$$C_{i1} = \max \left(\frac{R_{i1}}{\sum_{j=1}^3 n_j - 1}, \frac{Q_{i1}}{\sum_{j=1}^3 n_j + 1} \right) \quad (18)$$

Choose to add or remove machines in phase 2 based upon which will give the highest average throughput per machine.

$$C_{i2} = \max \left(\frac{R_{i2}}{\sum_{j=1}^3 n_j - 1}, \frac{Q_{i2}}{\sum_{j=1}^3 n_j + 1} \right) \quad (19)$$

Choose to add or remove machines in a phase 3 based upon which will give the highest average throughput per machine.

$$C_{i3} = \max \left(\frac{R_{i3}}{\sum_{j=1}^3 n_j - 1}, \frac{Q_{i3}}{\sum_{j=1}^3 n_j + 1} \right) \quad (20)$$

Of the possible machine changes recommended choose the option that will result in the highest overall average throughput per machine.

$$\max(C_{i1}, C_{i2}, C_{i3}) \quad (21)$$

These machine addition and removal rules apply to the system for one change in machine allocation. There is no foresight to determine what the optimal system will be. The same starting criteria will always result in the same final outcome.

5.5.5. Machine Interactions

Machine interaction refers to the activity or activity outcome of one machine affecting the activity or activity outcome of another machine. Machine interaction can either be direct or indirect. Direct interaction is an event where one or more machines are delayed by the activity of another machine; the machines are in direct contact. For a direct interaction to end, one or more machines must begin another activity. An indirect interaction is where one or more machines are delayed by the outcome of the activity of another machine; the machines may or may not be in direct contact.

The MA model evaluates systems for machine interactions. There are three forms of machine interaction that the MA model identifies:

1. Starvation – a machine has no inventory from which to draw.
2. Blockage – an inventory to which a machine is delivering the output of a cycle is at or above the maximum level and cannot accept any further inputs.
3. Congestion – the number of machines at a control point is above a maximum number resulting in one or more machines being forced to wait for one or more machines to depart the control point.

Interactions between different phases of the harvesting system are measured as blockage and starvation delays. Inter-phase delays occur as a result of indirect machine interactions. There is no close contact between the machines that results in the delays, the rate of operation of one machine is affecting the production of one or more other machines.

Interactions within the skidding phase of the harvesting system are dealt with using direct interactions described as congestion. The simulation of machine congestion occurs at two control points within the harvesting system. One control point where congestion occurs is the landing, which is a designated area of limited size and is used to

process, sort and store logs, and load trucks. The user can control the number of skidders that can be accommodated on the landing without interference. If the number of skidders on the landing reaches the maximum level as set, then skidders that subsequently arrive at the landing will enter a landing congestion delay state until there is space for them to enter the landing and complete the cycle. The maximum number of skidders on the landing has a possible range of one to five.

The other control point where congestion occurs is at the load acquisition point. A skidder enters an acquisition delay state if it arrives at the load acquisition point and there is already a skidder in the process of acquiring a load. This congestion state exists because there is assumed to be one acquisition point for any inventory and only limited capacity for machine movement and tree/log manipulation at the acquisition point.

5.5.6. Machine Delays

When a machine is in a machine interaction state it is delayed. Delay times and intervals are recorded for each machine interaction. To provide a more realistic simulation, the MA model has the capacity to include machine breakdowns. Breakdown delay is independent of the system configuration and the performance of the other machines, however is integral to the performance of the machine and can result in starvations or blockages forming. The breakdown delay type is designed to represent stoppages that occur in the operation of machinery as a result of mechanical failure of the machine or other equipment integral to the operation of that machine, and maintenance stoppages that occur at regular or irregular operating intervals.

An example of a breakdown delay for a motor-manual type feller is where the operator stops to sharpen the chain and loses some operating time to perform this maintenance. An example of a breakdown delay for a grapple skidder machine type is where the skidder stops operating for six hours because of a flat tire which must be fixed. The variability in probability of a breakdown occurring and the breakdown length, as demonstrated by these examples, is incorporated by having user-specified breakdown rates and breakdown length functions specific to each machine. Delays are generated randomly using a Monte Carlo method. When a breakdown occurs a delay length is

generated from a uniform random distribution of delay lengths. The machine remains in the delay state until the delay length time has been exhausted.

5.6. Simulation Length

The simulation length used in the MA model is set to 90 SMH. The model iterates based upon ten-second calculation intervals and performs a total of 32400 iterations (the maximum allowable in STELLA software).

The simulation length was chosen after analysis showed that it provided a long enough time observation period to provide accurate output that was reproducible, while still maintaining enough detail to simulate machine interactions. The analysis consisted of running the simulation ten times using different calculation intervals and the same parameter values. As a result of this analysis the relationship between calculation interval and coefficient of variation, in Figure 5.3 was produced.

The calculation interval and run length can be adjusted in the MA model to suit user preferences. The simulation length can be modified in two steps:

1. Select the “Run Specs...” menu item from the “Run” menu and adjust the length and iteration interval appropriately.
2. Navigate to the “Inputs” screen and adjust the “Iterations per Minute” input to the value specified in the “Run Specs...” menu item.

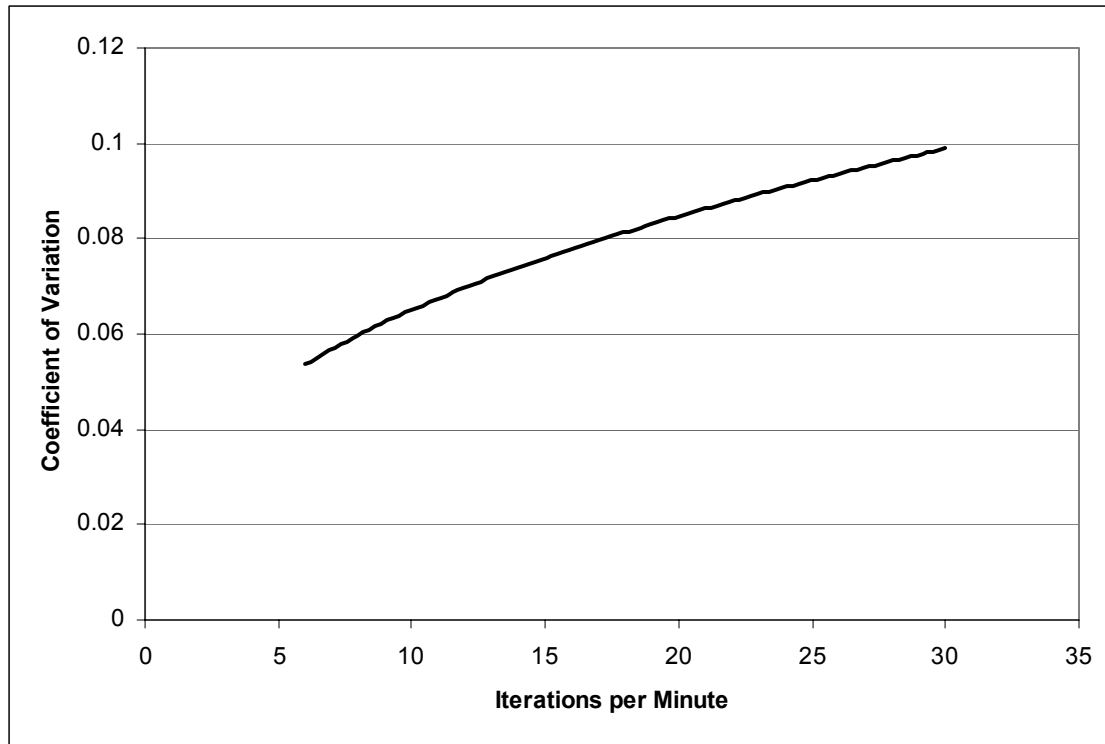


Figure 5.3. Effect of calculation interval (shown as Iterations per Minute) or DT on the coefficient of variation. Fewer iterations per minute results in longer calculation interval.

Figure 5.3 shows the effect of calculation interval on the coefficient of variation. The longer calculation interval allows a longer simulation to be run and provides a more reproducible output (lower coefficient of variation), however some detail is lost because of lower resolution in the machine sub-models.

The shorter calculation interval, with higher resolution, causes the felling machines to have a higher productivity. The productivity of the skidding and processing machines does not vary much between different simulation lengths. The cause of the higher felling productivity is that the system is still in a start-up phase and has not reached a steady pattern. In longer simulation lengths the fellers reach a blockage state before the simulation is half-way completed, in the short simulation the fellers reach the blockage state near the end of the simulation. The blockage state is the cause of the lower feller productivity in the longer simulations.

5.7. Outputs

The objective of the MA model is to develop a computer-based analysis tool to evaluate machine allocation decisions with respect to system and machine productivity and efficiency. The outputs must provide information in a way that can be used to meet these goals.

There are three parts to the outputs of the MA model:

1. Productivity
2. Delay/Interaction summary
3. Machine allocation and substitution

5.7.1. Productivity

Productivity information is presented to account for the performance of each machine and phase within the harvesting system. Productivity rates are reported by scheduled hour and productive hour. The productivity rates provide the foundation upon which the rest of the output is based. It is also a means for comparison whereby the output of the simulated harvest system can be compared with output from an existing system which the user is modeling.

5.7.2. Delay/Interaction Summary

The delay and interaction summary information is to focus user attention on the symptoms of inefficient machine combination. The MA model reports the mean delay length, mean interval between delays and the number of the delays that occur for each type of delay/interaction for each machine. The utility of this information is that it assists identification of where inefficiencies are entering the system. The user can infer based upon the number and interval of delays the severity of imbalance in the system. The delay/interaction summary is especially useful for inferring possible changes to the system. Congestion delays imply imbalance among system phases or poor assignment methods. Blockage and starvation delays infer directly which phases in the system are at an imbalance.

5.7.3. Machine allocation and substitution

The machine allocation output is a powerful feature of the MA model. Based upon system balance the MA model provides suggestions as to which machines it is most advantageous to add or remove from the system. The suggestions are based purely upon the results of the simulation and are applicable for only addition or removal of a machine. The MA model is designed for iterative use, such that at the end of each simulation the user can make changes to the machine combination and evaluate the changes. The goal is that as a result of iterative changes, the system will be better balanced subject to the same general system and site parameters.

There is no cost component to the MA model to determine the value of changes to the system. The value is assessed in terms of technical effectiveness.

CHAPTER 6. MODEL VALIDATION

6.1. HSA Model

The aim of model validation is to determine the usefulness of the model for the purposes for which it was designed (Stermann 2000). The purpose of the HSA model is to assist users assign systems to stands. To these ends, the validity of the HSA model must be evaluated on its usefulness to provide information to assist with system assignment decisions. Validity in this case is a measure of the ranking accuracy of the HSA model as opposed to the absolute measurements of productivity and efficiency that the model provides.

Evaluation of the validity of the HSA model is performed using two ranking-based indexes:

1. Different systems on the same site
2. The same system on different sites

The evaluation was conducted using published production studies as source information for site, stand and system inputs. None of the production studies used in validation were used in the data set that the model is based upon. The HSA model was run ten times at a run length of 500 SMH (see Section 4.7) for each combination of inputs and the outcome from the HSA model was then compared with the published production rates.

Table 6.1 shows the ranking difference and the associated score. The various input combinations were ranked based upon published productivity data. The output from the HSA model was ranked in the same manner and the difference in ranking between the HSA output and the ranking for published data is then the Ranking Difference in Table 6.1. An example of how the ranking scores are applied is shown in Table 6.2.

Table 6.1: Ranking scoring schedule for validation of HSA model. “Ranking difference” is the variation in rank place between published studies and HSA model output. “Score” is the score associated with each “ranking difference.”

Ranking Difference	Score
Same	1
± 1	0.5
Other	0

Table 6.2. Ranking scoring example.

System	Literature	MA model	Ranking Score
A	1	1	1.00
B	2	3	0.50
C	3	2	0.50
Average Ranking Score			0.67

6.1.1. Site Ranking

Table 6.3: Ranking validation scores for site ranking of harvesting systems.

Comparison	Score	Reference
Evaluation of a Shovel system on five sites	0.60	Andersson 1997
Evaluation of a Cut-To-Length system on six sites	0.58	Spinelli et al. 2002
Evaluation of a Manual system on three sites	1.00	Kluender and Stokes 1994
Average site-ranking index	0.73	

6.1.2. System Comparison Ranking

Table 6.4: Ranking validation scores for system ranking of harvesting systems

Comparison	Score	Reference
Cut-To-Length and Mechanized systems	0.5	Lanford and Stokes 1996
Manual and Cut-To-Length systems	1.0	Klepac and Rummer 2002
Mechanized and Cut-To-Length systems 1	0.5	Hartsough et al. 1997
Mechanized and Cut-To-Length systems 2	0.5	Hartsough et al. 1997
Cut-To-Length and Manual systems 1	1.0	LeDoux and Huyler 2000
Cut-To-Length and Manual systems 2	1.0	LeDoux and Huyler 2000
Average system comparison ranking index	0.75	

A ranking score of 1.0, means that on average the HSA model output gave the same ranking as the literature to which it was compared. A ranking score of 0.5 means

the HSA model gave a ranking that was off by one from the ranking in the literature to which it was compared.

The above results show a ranking index of 0.73 and 0.75 indicating a strong relationship between the ranking from the literature and the ranking from the HSA model.

These ranking indexes describe the ranking accuracy of the HSA model. They infer that approximately three out of four times the ranking provided by the HSA model will be the same as the ranking from recorded observations of working systems.

6.2. MA model

6.2.1. Machine Reallocation

The MA model was evaluated for effectiveness in making machine allocation decisions. A series of 30 simulations were run at a run length of 90 SMH (Section 5.6) to determine the accuracy of the MA model prediction. The recommended machine allocation decisions were made and the predicted throughput compared with the actual throughput per machine.

Table 6.5: Average percentage deviation of estimated from actual productivity by machine phase, add/remove machine and total. Positive value represents overestimate, negative value represents underestimate.

	Add	Remove
Felling	35.98	-2.81
Skidding	-8.57	2.00
Processing	5.70	9.09

The MA model overestimated in 53 percent of machine allocation estimates. There were two instances in which the MA model was exactly correct in its prediction.

While not exact, the MA model on average gives a relatively accurate prediction of the productivity that will result from a machine allocation change. The largest inaccuracies can sometimes be anticipated by user intuition. The largest inaccuracies are most often caused when adding a very high productivity machine such as a feller-buncher. These instances typically occur when the phases in a system are close to balanced and the bottleneck is at the start of the system in the felling phase.

The ability of the MA model to predict the effect of machine additions and removals is key to determining the effectiveness of incorporating real-time information technology into harvesting systems. The accuracy of the MA model shows that the MA model generally produces a good estimate of the effect of changes in machine combination.

6.2.2. System Comparison

Validation of the MA model also requires comparison of the model effectiveness in reproducing the results from production studies evaluating machinery production potentials and interactions. Production studies that characterize the performance of the machines within the system in terms of utilization are needed to give a complete comparison. There are few production studies that meet the needs for such an evaluation of the MA model, limiting the comprehensiveness of this validation. However, comparison of PMH productivities of machines will allow for bottleneck identification which is sufficient for low level comparison with the output of the MA model.

To develop a state-based machine model such as the MA model, a database of cycle time functions are required. The empirical nature of cycle time functions is such that, each cycle time function for a machine is a summary of how a particular machine performed, when operated by a particular person on a certain site. There are two possible approaches to alleviate the bias that is introduced:

1. A comprehensive set of cycle time functions that will apply to any machine on any site.
2. One set of generalized functions that are formed from the database and are not specific to any particular instance but in general are a good approximation of most combinations.

The second approach - generalized functions - was used in the MA model to determine appropriate cycle times.

Validation is performed on a case study basis comparing results to system studies that were not part of the production function synthesis for the MA model.

6.2.3. Case study #1: Tigercat productivity study (Visser and Stampfer 2000)

System description

This is a mechanized thinning system studied on the coastal plain of North Carolina. The machinery allocated to the system consisted of:

Tigercat 720B feller-buncher

Tigercat 630 grapple skidder

Timberjack 380C grapple skidder

Timberjack 450B grapple skidder

Tigercat 245 tracked loader

Tigercat 245 tracked loader

CTR 400 static delimber

CTR 500 static delimber

The Tigercat system layout had the feller-buncher prebunch stems after felling for subsequent skidding. Two skidders transported the bunched stems from the stump to the landing, the other skidder was kept as a reserve. At the landing there were two inventories to which skidders could deliver loads. The loaders operating with the static delimiters worked from the inventories to process the delivered stems into logs.

The landing is a key control point in this system because it involves a large proportion of machine interaction. There is interaction between the skidders and the loaders, and the possibility for skidder congestion to occur.

The MA system layout has the feller-buncher at the head of the system working a felling pattern where it is moving away from the landing and felling up to a maximum skid distance of 1000 feet. The skidders are assigned to the single felled inventory, this creates the chance of congestion delays occurring for skidders when acquiring stems. The skidders deliver the loads to either inventory at the landing. The maximum skidded inventory at the landing is set to 15 tons total so that the skidders do not swamp the processors.

Table 6.6: Productivity (tons/PMH) of system phases for the Tigercat and associated MA harvesting system.

Harvesting Phase	Tigercat System (Visser and Stampfer 2000)	MA model
Felling	37	35
Skidding	58	41
Processing/Loading	27	18

Table 6.4 shows that the ranking produced by the MA model is the same as the results from the study it was simulating. The magnitude of the productivities from the MA model are less than the observed productivities in Visser and Stampfer (2001). The most significant deviation in magnitude is for the skidding phase which is 17 tons per PMH lower than the actual system. The lower skidder productivity is attributable to sub-optimal load sizes acquired by the skidder in the MA model. The MA model calculates the skidder load size based upon the number of trees per load and the DBH. As the piece size decreases the number of stems per load increases, however the increase in the number of stems per load does not compensate fully for the loss in volume caused by decreased piece size. The maximum load size for grapple skidders is 3.5 tons. The average piece size during the MA model simulation of the Tigercat harvesting system was 2.2 tons. If the load size had been optimized for the skidders, the skidder productivity from the MA model would have been 66 tons per PMH.

The difference in Processing/Loading productivity is attributable to the fact that the closest machine approximation was used in the MA model because there is no loader-processing machine available. The approximation used was a processor, which in the MA model is defined using productivity information from single-grip processors and stroke delimiters.

Table 6.7: Delay summary for skidder 1 from MA model simulation of Tigercat harvesting system with landing storage set at 15 tons

Delay Type	Mean Length (min.)	Count	Interval (min. betw. delays)
Blockage	7.8	37	6.8
Breakdown	12.2	4	122.8
Congestion	14.5	3	165.4
Starvation	0.4	2	269.6

Table 6.8: Delay summary for skidder 2 from MA model simulation of Tigercat harvesting system with landing storage set at 15 tons

Delay Type	Mean Length (min.)	Count	Interval (min. betw. delays)
Blockage	7.9	39	5.9
Breakdown	4.1	3	175.9
Congestion	20.1	2	249.9
Starvation	0.4	2	269.6

The delays that were experienced by the skidders during the simulation show that the most limiting machine interaction was blockages (Table 6.7, Table 6.8) that were caused by a large inventory forming at the landing ahead of the loaders/processors. The processing machines were operating at a rate that was much lower than the rate at which skidders were able to deliver wood to the landing.

To improve the Tigercat harvesting system Visser and Stampfer (2000) suggest maintaining a higher skidded inventory on the landing. By storing more skidded volume on the landing, in the event of a skidder breakdown the loaders will continue working and not be starved. To test the effect of higher skidded inventory allowance on the system, another simulation was conducted with the total skidded inventory limit increased from 15 tons to 100 tons.

The larger landing storage for skidded wood resulted in significant decreases in the amount of blockage time for the skidders (Table 6.9, Table 6.10). The landing storage increase created a buffer that allowed the skidders to work for longer before the landing was filled and delays started occurring. The effectiveness of the loaders was not changed by the increase in landing storage. In reality the effectiveness of the loaders would probably decrease slightly because they would be required to perform movement and extra manipulation of the logs unless some coordination with the skidders was

implemented for moving wood on the landing. The loaders are still limiting to the operation and to improve the system balance either loader/processor capacity must be increased or the skidding capacity reduced.

Table 6.9: Delay summary for skidder 1 from MA model simulation of Tigercat harvesting system with landing storage set at 100 tons

Delay Type	Mean Length (min)	Count	Interval (min. betw. delays)
Blockage	5	8	62
Breakdown	44	5	64
Congestion	0	0	0
Starvation	1	1	539

Table 6.10: Delay summary for skidder 2 from MA model simulation of Tigercat harvesting system with landing storage set at 100 tons

Delay Type	Mean Length (min.)	Count	Interval (min. betw. delays)
Blockage	5	11	44
Breakdown	29	4	106
Congestion	3	3	177
Starvation	1	1	539

6.2.4. Case Study #2: Comparison of Mechanized Systems for Thinning Ponderosa Pine and Mixed Conifer Stands (Hartsough et al. 1997)

This is a study of three types of harvesting system on pine plantations and naturally-regenerated conifer stands. Two conventional harvesting system arrangements and a hybrid system are compared.

Harvesting system machine allocations:

Whole-tree system:

- Timbco T420 feller-buncher
- Timberjack 450B grapple skidder
- Caterpillar 528 grapple skidder
- Timberjack 90 stroke delimber

Cut-to-Length system:

- Timberjack 1270 harvester
- Timberjack 1010 forwarder

Hybrid system:

- Timbco 420 feller-buncher
- Timbco T435 harvester
- Timberjack 450B grapple skidder
- Caterpillar 528 grapple skidder

There is no productivity information provided for any of the harvesting systems. They are instead compared on a cost per unit of production basis. Cost calculation is not included in the MA model so any such direct comparison is not feasible. Hartsough et al. (1997) ranked the harvesting systems in terms of cost per thousand board feet (\$/MBF). This analysis using the MA model will rank the harvesting systems in terms of productivity and cost per ton.

Table 6.11: MA model productivity output for Whole-tree harvesting system

Machine	Productivity (tons/PMH)
Feller-buncher	52.7
Skidder 1	34.3
Skidder 2	32.0
Processor	16.2

The whole-tree harvesting system experienced significant blockage delays to the skidding and felling phases of the operation as a result of the bottleneck caused by the low processing capacity (Table 6.11). The felling and skidding phases are well balanced; the improvement that is most appropriately made is an increase in the processing capacity. Either processing machines can be added until the processing capacity is closer to the felling and skidding capacities, or a skidder can be removed and a processor added. If processing capacity is increased the system will have a productivity of close to 50 tons/PMH after the addition of two processing machines. By removing a skidder and adding a processor the system will have the same amount of machinery and productivity will increase to approximately 30 tons/PMH.

Table 6.12: MA model productivity output for Cut-to-Length system

Machine	Productivity (tons/PMH)
Harvester	29.4
Forwarder	26.6

The cut-to-length system was well balanced. There were no machine interaction delays. The productivity of the harvester was high enough that it built a buffer inventory ahead of the forwarder so that when the harvester broke down the forwarder still had sufficient inventory to draw from and was not starved. There were no machine allocation changes that could be made to this system to improve it.

Table 6.13: MA model productivity output for hybrid system

Machine	Productivity (tons/PMH)
Feller-buncher	52.2
Harvester	29.5
Grapple skidder 1	29.1
Grapple skidder 2	31.5

The hybrid system is very high productivity by comparison to the whole-tree and cut-to-length systems. There is no processing phase in the hybrid system because sawlogs are processed by the harvester and pulp logs are delivered in long lengths to a chipper which cannot be modeled in the MA model. The productivity of the skidding phase is the bottleneck in this system. Because of limitations on the flexibility of the MA model there were no improvement suggestions available to improve the harvesting system. The utilization of the skidders was 55 percent. The skidder assignment method was on a largest inventory basis. Congestion at the acquisition point resulted in a total of 79 minutes of congestion delays. The congestion delays suffered by the skidders caused much of the decrease in utilization, thus a more intelligent assignment regime would probably increase skidder utilization and in turn system productivity. An attempt to prove this was made by changing the assignment regime for skidder 1 to fixed assignment to the feller-buncher, and skidder 2 was assigned on a largest inventory basis.

By changing the skidding assignment regime, the number of skidder congestion delays decreased. As a result of the decreased congestion delays the skidding productivity improved by 11 percent to 50.2 tons per SMH.

Table 6.14: Unit cost comparison between MA model output and Hartsough et al. (1997)

System	Productivity in tons/SMH (MA model)	Cost per ton (\$) (MA model)	Cost per SMH (\$) (Hartsough et al. 1997)	Cost per MBF (\$) (Hartsough et al. 1997)
Whole-tree	12.7	20.79	264	210
Cut-to-length	18.5	11.30	209	220
Hybrid	43.2	6.53	282	160

Table 6.14 holds the data used to develop the standardized cost per unit. The productivity from the MA model in the second column is combined with the hourly cost information in the fourth column to determine the cost per ton.

The processing machine had the most limiting production rate in the whole-tree system (Table 6.11). The high cost of the whole-tree system (Table 6.14) is attributable to underestimation of the productivity of the processing machine by the MA model. The hybrid system had no processing component in the MA model analysis because processing was carried out at the stump by the harvester. The hybrid system productivity

appears to have been overestimated by the MA model explaining the relative difference in magnitude of the cost per unit between the hybrid system and the other two systems.

Table 6.15: Standardized cost per unit comparison between MA model and Hartsough et al. (1997) for three harvesting systems.

System	Standardized Cost per Unit (MA model)	Standardized Cost per Unit (Hartsough et al. 1997)
Whole-tree	1.84	0.95
Cut-to-Length	1.00	1.00
Hybrid	0.58	0.73

The output of the MA model is compared with the information published in Hartsough et al. (1997) using a standardized cost per unit (Table 6.15). The assumption that; the output for the cut-to-length system is equivalent for both the MA model and Hartsough et al. (1997), is made to determine a benchmark to allow comparison between the systems. The cut-to-length system is chosen because it is the simplest system arrangement having only two machines and one possible machine interaction combination - harvester/forwarder. By comparison the Whole-tree system has four machines with five different machine interaction combinations:

1. Feller-buncher/Skidder 1
2. Feller-buncher/Skidder 2
3. Skidder 1/Skidder 2
4. Skidder 1/Processor
5. Skidder 2/Processor

The hybrid system has four machines and five (four using fixed and largest inventory skidder assignments) machine interaction combinations:

1. Feller-buncher/Skidder 1
2. Feller-buncher/Skidder 2
3. Harvester/Skidder 1 (does not occur with fixed and largest inventory skidder assignment combination)
4. Harvester/Skidder 2
5. Skidder 1/Skidder 2

Thus the simplest system was chosen as the benchmark system and the more complicated systems with greater possibilities for more, and different types of delays were compared to the benchmark systems.

From the comparison in Table 6.15, the MA model produced output that had a much wider range than the information from Hartsough et al. (1997) supported. This however can be attributed to the underestimation of the processor capacity by the MA model. The delay summary feature of the MA model will allow the user to gain insights into systems such as those described in Hartsough et al. (1997) and determine what are the likely causes of machine interaction inefficiency and what type of interaction is most limiting to the system.

CHAPTER 7. EXAMPLE SIMULATIONS

Chapter 7 provides analytical evidence of the behavior of the HSA and MA models, as well as demonstrating the usefulness of each model to the user for the purposes for which each was designed.

7.1. HSA Model

The purpose of this analysis of the HSA model is to demonstrate the utility of this model to support system assignment decisions. There are many possible combinations of site, stand and system parameters that can be examined. To provide structure to this analysis, the general default parameter values are used as a basis for comparison.

Table 7.1: Default parameter input values used for example simulations of HSA model:

Input	Value
Maximum Skid Distance (ft)	800
Stand Size (tons)	5000
Scheduled Hours per Day	9
Probability of One Delay per Hour	0.2
Maximum Tons of Product Storage on Landing	150
Minutes Between Truck Arrivals	60
Truck Payload (tons)	25
Loading Rate (tons/hour)	50
DBH (min., mean, max., std.dev.)	8, 14, 20, 2
Slope (min., mean, max., std.dev.)	-15, 0, 15, 5
Stocking (min., mean, max., std.dev.)	450, 500, 550, 20
Harvest Intensity	1

The default parameter values in Table 7.1 specify an average harvest slightly beyond the optimal range for the four harvesting systems. With this parameter value set, all systems will perform relatively well but still be limited enough to provide a realistic output that would be similar to the average productivity and costs for actual systems.

Table 7.2: Default cost input values for example simulations of HSA model.

System	Fixed Cost (\$/hour)	Variable Cost (\$/hour)
Manual Felling Cable Skidding	100	60
Mechanized Felling Grapple Skidding	150	100
Shovel Bunching Grapple Skidding	160	125
Harvester and Forwarder	170	100

The cost values in Table 7.2 were set based upon cost information found in literature (Hartsough et al. 1997, Tufts and Brinker 1993, Tufts 1997, Lanford and Stokes 1996, Richardson and Makkonen 1994).

In this analysis the systems will be referred to in short to avoid wordiness:

Manual Felling Cable Skidding = manual system

Mechanized Felling Grapple Skidding = mechanized system

Shovel Bunching Grapple Skidding = shovel system

Harvester and Forwarder = cut-to-length system

7.1.1. Impacts of skid distance on the harvesting system

Incremental analysis was performed to evaluate the effect of changes in the value of the parameter “Maximum skid distance in feet” on the performance of each of the harvesting systems. Inputs for all other parameters were maintained at the default values in Table 7.1 and Table 7.2.

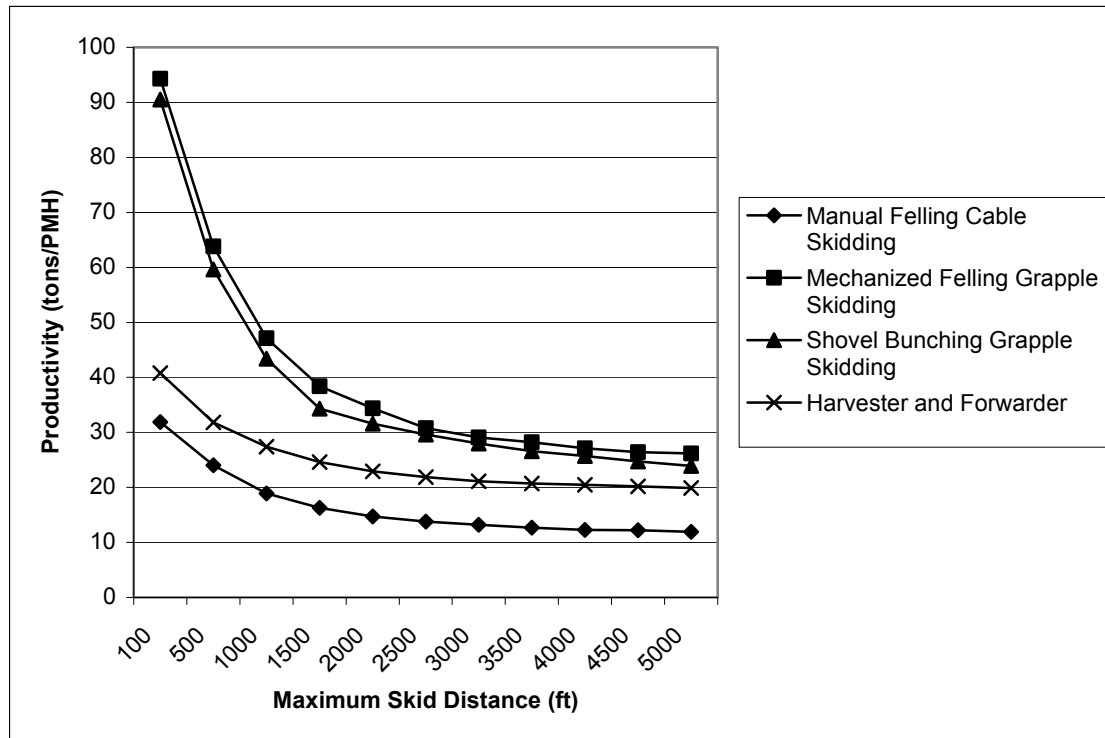


Figure 7.1: Productivity of the four harvesting system types in the HSA model as a function of Maximum Skid Distance.

System productivity for the four types of harvesting system in the HSA model all have similar tendencies with respect to skid distance. For short skid distances productivity is very high, as the skid distance increases, productivity decreases at a declining rate. The key features of the shape of the productivity curves are the lower productivity tendencies of the manual system and cut-to-length system from the remaining two systems. The manual system and cut-to-length system are represented as having a lower productivity at the lowest value for maximum skid distance of 100 feet because these systems are typically more intensive in the accumulation element of the cycle because each tree/log is treated individually. The productivity curves for these two systems are less responsive to skid distance because the relative contribution of travel time to the total cycle time for these two systems is lower than in the mechanized and shovel systems.

7.1.2. Impacts of site parameters on the harvesting system

Incremental analysis was performed to evaluate the effect of changing values for various site and stand parameters on the effectiveness of harvesting systems. For each analysis, the parameter of interest is varied, while, the values for all other parameters are set at the default values (Table 7.1, Table 7.2).

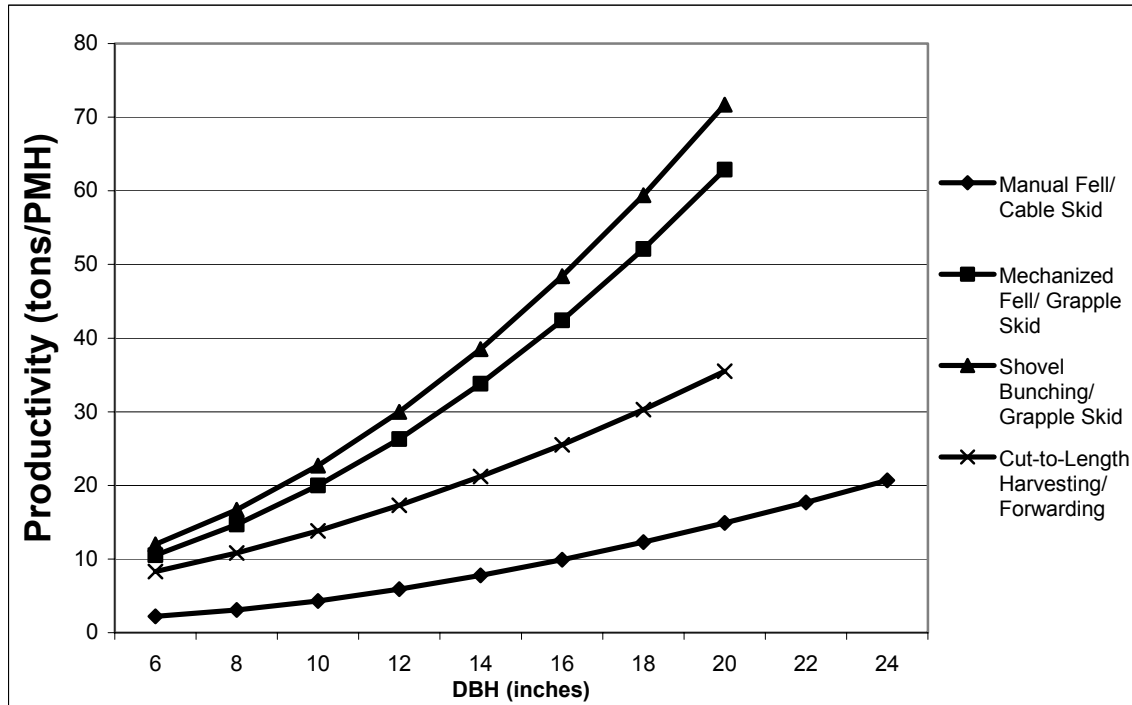


Figure 7.2: Piece size productivity curves by harvesting system type over a range of DBH values with all other parameters set to default values.

Figure 7.2 illustrates the tendency of each system as it responds to the piece size parameter (DBH). The shape and magnitude of the piece size function varies with system type. The utility of Figure 7.2 is that it shows relatively which systems are more responsive to changes in piece size and at any value of piece size which system is the most productive. A key feature of Figure 7.2 is the end to the productivity curves for the three systems that utilize mechanical felling (mechanized, shovel and cut-to-length systems), whereas the manual system is not limited by a maximum piece size and thus the curve continues on beyond those of the mechanical felling systems.

The manual system is the most sensitive to piece size, while shovel/mechanized systems are the least sensitive.

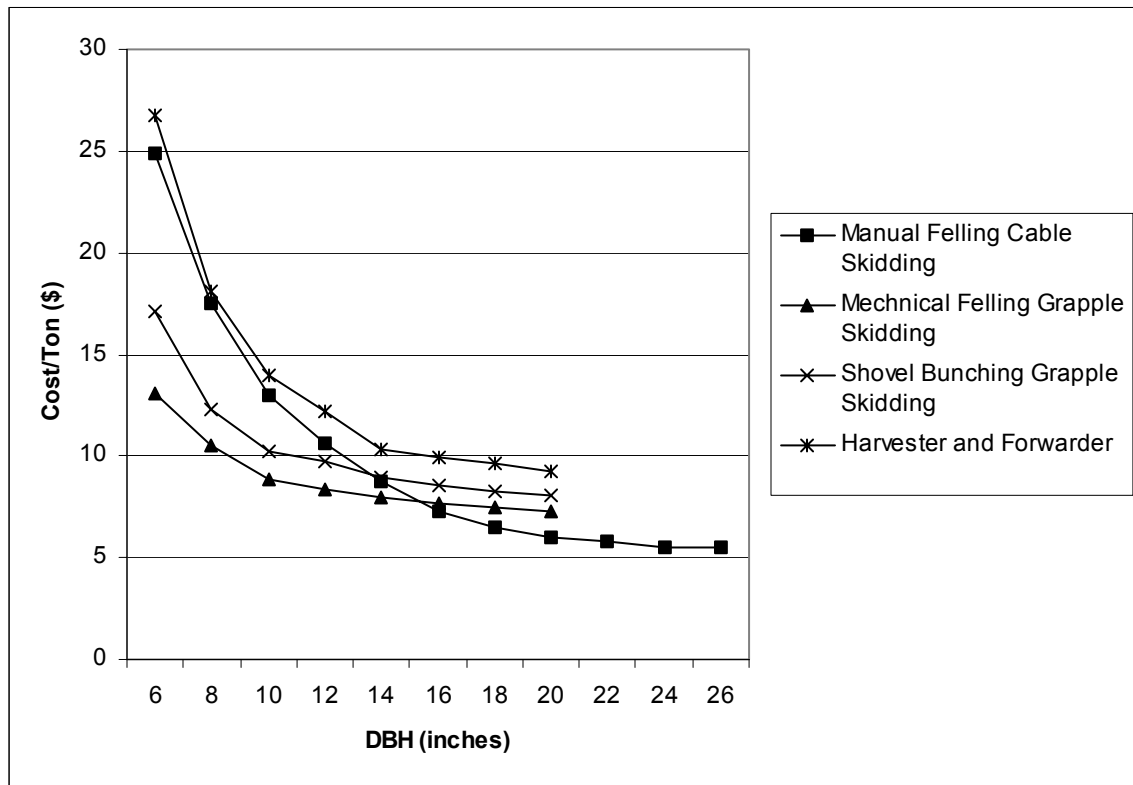


Figure 7.3: Cost per unit (\$/ton) for the four harvesting system types defined in the HSA model over a range of DBH values with all other parameters set to default values.

Productivity output is only one indication of system effectiveness. The cost per unit of production is a key metric that is used to define the effectiveness of a system. In a capitalistic environment where a goal of management is cost minimization the HSA model can be used to rank systems for the lowest cost option. Lowest cost ranking is a more appropriate measure of effectiveness of a system than productivity ranking because unit cost takes more factors into account, including productivity which is a factor in the cost per unit determination for a system.

From unit cost output information it is possible to develop a lowest cost frontier. Figure 7.3 illustrates how the cost per ton varies with changes in productivity, where productivity is influenced by DBH. Each system displays a unique curve in terms of shape and magnitude, this shape is totally dependent on the production potential and the productivity functions used to transform parameter values into effects on productivity. By

overlaying the various system production curves a lowest cost option is available for each value of DBH. This is the lowest cost frontier for this particular set of parameter values. The lowest cost frontier for the set of unit cost curves in Figure 7.3 is mapped specifically in Figure 7.4.

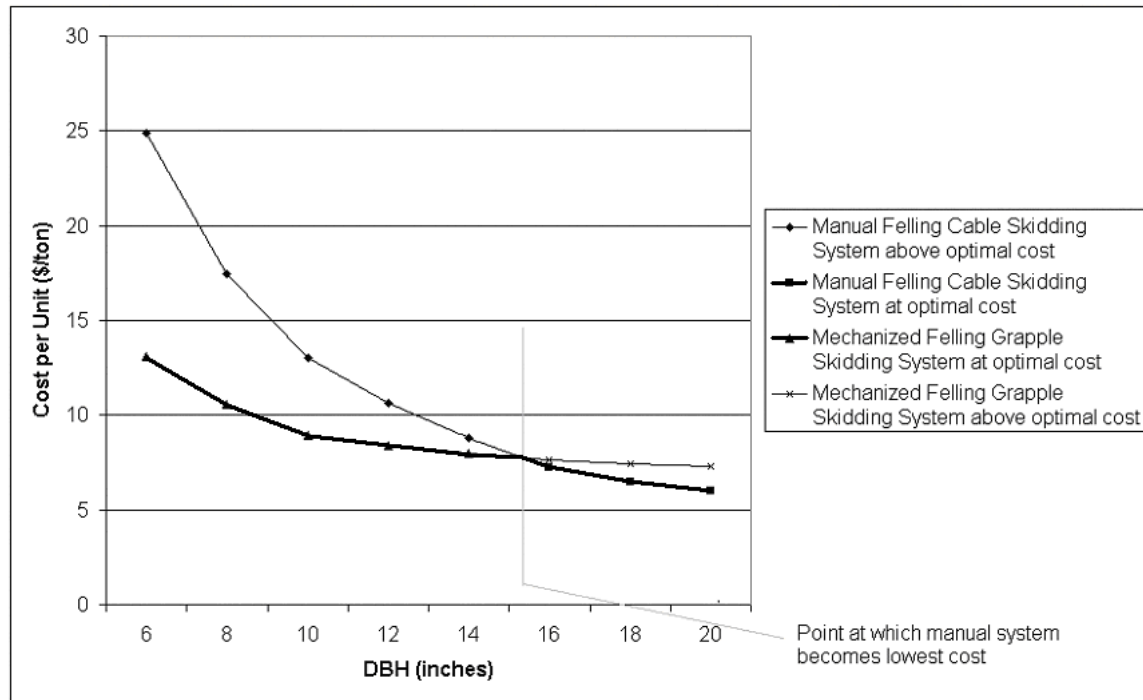


Figure 7.4: Lowest cost frontier for all harvesting system types over a range of DBH values with all other parameters set at the default level.

The accuracy of the HSA model is only as good as the inputs upon which a simulation is based. The output from the HSA model that is of most utility is the system represented at the lowest cost frontier rather than the values of the lowest cost frontier. The most cost-effective system is determined by identifying the lowest cost frontier and the system that defines the lowest cost frontier at the parameter range of interest.

When the parameter values are deterministic, the outcome can be calculated with a high level of precision. In Figure 7.4, as the DBH parameter value increases there is a point close to 15 inches DBH at which the manual system becomes the lowest cost alternative, whereas, at DBH parameter values below 15 inches the mechanized system is the lowest cost alternative. In actuality, for most instances the parameter values will not be as clearly defined as the example presented (Figure 7.4) because DBH values in actual

stands tend to vary, so an expected value of DBH would be required to produce a figure similar to the Figure 7.4. The HSA model uses the distribution inputs for some site and stand parameters to examine the effect of variability on harvesting systems.

A powerful feature of the HSA model is the Cost of Inefficiency calculation. It provides insight into the relationship between site, stand and system parameters, and cost per unit. If all parameter values were within the optimal range for a system, it would operate at its maximum rate and have the lowest (or optimal) cost per unit. Due to assignment inefficiencies, a system will be limited by one or more parameters. This limitation will reduce the productivity of the system, and in turn increase the cost per unit. The difference in estimated cost per unit over a systems theoretical optimal cost per unit is caused by one or more of the parameters limiting the system production rate. The HSA model determines how much of the difference between estimated cost per unit and optimal cost per unit is attributable to each parameter.

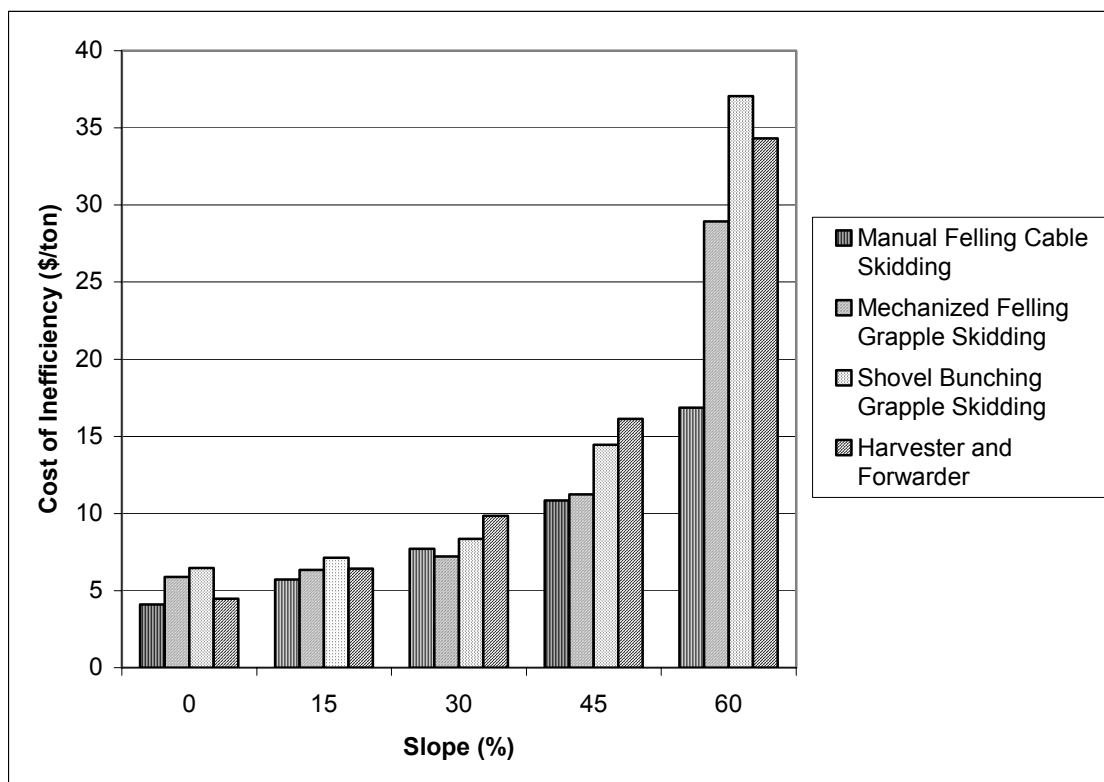


Figure 7.5: Impact of Slope parameter on Cost of Inefficiency for each of the four harvesting systems in the HSA model.

The Cost of Inefficiency as affected by Slope is illustrated in Figure 7.5. The estimated cost per ton can be calculated by simply adding the optimal cost per ton to the estimated Cost of Inefficiency. The lowest cost system must be chosen using the estimated cost per ton.

The value of the Cost of Inefficiency is that the limiting effect of parameters can be identified and quantified. Figure 7.5 illustrates how individual systems are affected by the Slope parameter, and relatively how significant the impact of Slope is on the cost per unit for a system. When Slope is less limiting all systems are similarly comparable, however the manual system is much less impacted by Slope than the other three systems at higher Slope parameter values.

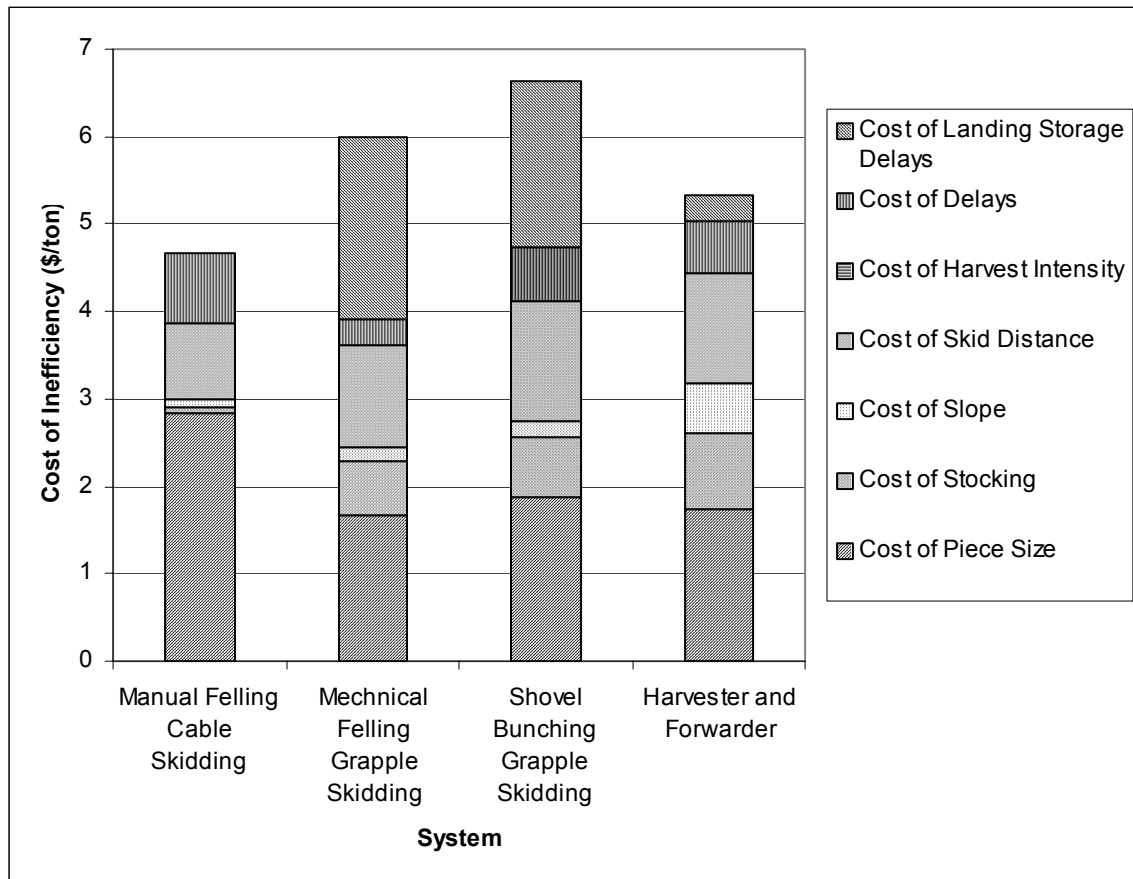


Figure 7.6: Cost of Inefficiency by harvesting system for default parameter values.

The Cost of Inefficiency is presented in a parameterized format by the HSA model in Figure 7.6. The parameterized format allows the user to determine which parameter is having the most significant effect on the production rate of the system.

The Cost of Inefficiency provides feedback to the user, it does not show which system is lowest cost, but it does show the magnitude of the impact of assignment inefficiencies on unit cost. In Figure 7.6, the manual system has the lowest Cost of Inefficiency, but the Piece Size causes most of the Cost of Inefficiency. The other three systems have a much lower cost of Piece Size relative to the overall Cost of Inefficiency. The manual system is in this instance limited most by the Piece Size, the other three systems are also limited by Piece Size but not as severely.

The parameter Stocking is limiting to all systems (Figure 7.6) but much less significantly so in the manual system than the other three systems. The parameters Slope, Skid Distance and Delays also add to the costs of production for all systems. Harvest Intensity was set at 1.0 for this example (Figure 7.6, Table 7.1, Table 7.2) which is within the optimal range for all systems and thus it adds no cost to production and is not featured on the Cost of Inefficiency in Figure 7.6.

A noticeable difference between the manual system and the other three systems in the Cost of Inefficiency (Figure 7.6) is the absence of a cost of Landing Storage Delays. Landing Storage Delays occur when a system is delivering wood to the landing at a much greater rate than it is being removed by trucking, the result is that the landing storage capacity becomes full and the harvesting system must enter a delay state until storage capacity is available. The manual system delivered wood to the landing throughout the simulation at a rate below the trucking removals rate from the landing. Thus the system never experienced any Landing Storage Delays. This occurred as a function of the particular rate at which the trucking was scheduled, the production potential of the manual system and the limiting effect of parameters such as the Piece Size on the production rate of the system. The other three harvesting systems operated with the same truck scheduling as the manual system, however, higher production potentials caused landing storage delays. The Cost of Inefficiency of all four systems would be comparable if an adjustment to the trucking capacity could be made. However the adjustment in trucking capacity would not result in simply removing the Landing Storage Delays

component from the Cost of Inefficiency because there is an interaction that exists between the various parameters. By reducing the cost of Landing Storage Delays, there will be a marginal decrease in the effect of other parameters also. The interaction is best shown by plotting the Cost of Inefficiency for one system with changing parameter values.

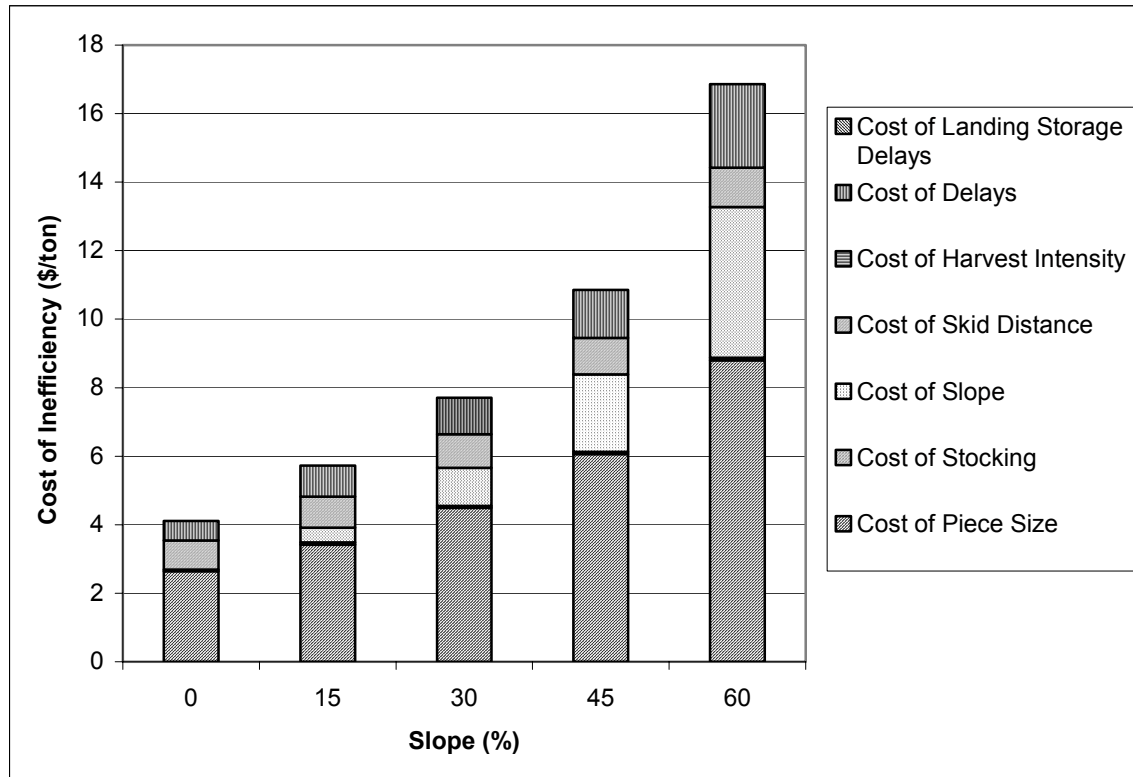


Figure 7.7: Parameterized Cost of Inefficiency for manual harvesting system – Slope values varied while all others set to default values (Table 7.1, Table 7.2).

The parameterized Cost of Inefficiency for a manual system is illustrated in Figure 7.7. As was demonstrated in the Cost of Inefficiency graph (Figure 7.5) as Slope increases, it becomes more limiting on production and the Cost of Inefficiency increases. What is also shown in the parameterized version of the Cost of Inefficiency graph (Figure 7.7) is that the increase in cost is not singularly attributable to the increase in Slope. An interaction is demonstrated in Figure 7.7. For each level of Slope, the Piece Size contributes most significantly to Cost of Inefficiency and the absolute contribution of this and other parameters increases as the Slope value increases. A similar effect is

demonstrated in Figure 7.8, however, because Piece Size is less limiting to the cut-to-length system, the increase in cost of Piece Size is much less than for the manual system.

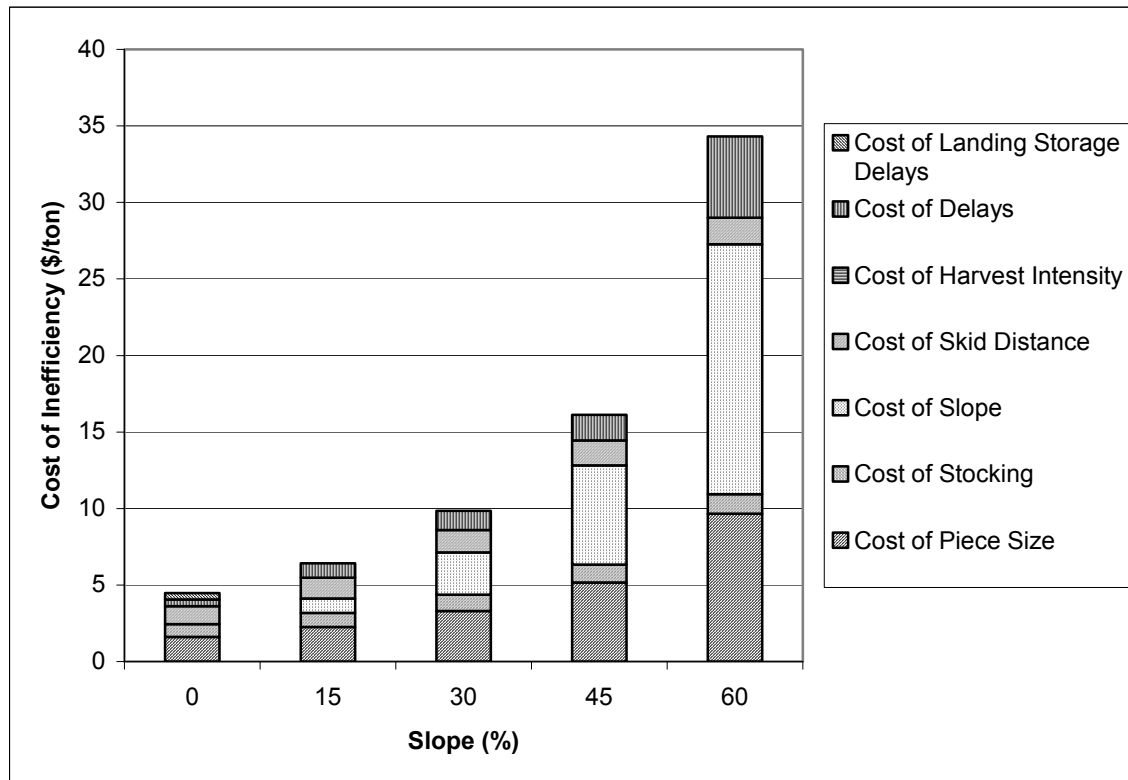


Figure 7.8: Parameterized Cost of Inefficiency cut-to-length system – Slope values varied while all others set to default values (Table 7.1, Table 7.2).

The cut-to-length system (Figure 7.8) is less sensitive to Piece Size (when the Piece Size is small) than the manual system (Figure 7.7), instead the cut-to-length system is relatively very sensitive to Slope, when the Slope becomes large.

From Figure 7.7 and Figure 7.8, it is evident that given this particular set of input values (Table 7.1, Table 7.2), the key variable for manual systems is the Piece Size and for cut-to-length systems is the site Slope. The implication of this is that manual systems perform better on stands with larger Piece Size and can be managed with some flexibility with regard to site Slope. Conversely, cut-to-length systems complement the manual systems by having flexibility with respect to Piece Size but are limited more severely by site Slope.

The effect one or more site, stand and system parameters can be estimated using the HSA model. The effect of a parameter on the system can be estimated in terms of the productivity, efficiency and cost of the system. This allows the HSA model to be used to compare two or more systems on a particular site or a particular system on two or more sites to determine the most appropriate assignment regime.

7.1.3. Example of Practical Application of the HSA model

The HSA model is designed as a practical tool to gauge the effects of harvesting system assignment decisions on the effectiveness of harvesting systems. An example follows to illustrate the utility of the HSA model in performing the functions for which it was designed. The scenario chosen is the decision of which type of system is best suited for harvesting a particular stand.

The example simulation is a thinning of a pine plantation on undulating terrain. The parameter values are specified in Table 7.3

Table 7.3: Input parameter values for example simulation of thinning of a pine plantation on undulating terrain.

Parameter	Value	
Maximum Skid Distance (ft)	1000	
Stand Size (tons)	5000	
Scheduled Hours per Day	9	
Probability of One Delay per Hour	0.2	
Maximum Tons of Product Storage on Landing	150	
Minutes Between Truck Arrivals	60	
Truck Payload (tons)	25	
Loading Rate (tons/hour)	50	
DBH (min., mean, max., std.dev.)	10, 12, 14, 1	
Slope (min., mean, max., std.dev.)	-15, 0, 15, 5	
Stocking (min., mean, max., std.dev)	450, 500, 550, 20	
Harvest Intensity	0.2	
Cost Inputs	Fixed Cost (\$/SMH)	Variable Cost (\$/PMH)
Manual Felling Cable Skidding	100	60
Mechanized Felling Grapple Skidding	150	100
Shovel Bunching Grapple Skidding	160	125
Harvester and Forwarder	150	80
Setup Cost	1500	

This simulation is designed to represent a stand harvest that could be encountered on upper coastal plain or piedmont physiographic regions in the southeast United States. The scenario for this simulation is that a stand is scheduled for harvest and as part of the tactical planning for a region a forester must determine which of four general system types is most appropriate for this particular harvest site. The best system for each site in an estate can be determined and used to formulate a harvest system assignment schedule.

The stand and site information for this particular harvest are determined from database information and the appropriate system production rates and costs are estimated as best as possible. To circumvent the possibility of trucking delays occurring in the simulation an overcapacity of trucking is scheduled, the extra trucking capacity in the HSA simulation is of no interest in initially determining the system assignment if trucking can be scheduled later using another model such as the LTSS. If there is a

limited trucking capacity available, and it is known initially, then this can be specified in the HSA model. In this example, the assumption is that trucking will be scheduled later.

The parameter inputs were entered into the HSA model and each of the four harvesting systems evaluated to determine the most appropriate system assignment decision for this stand.

Table 7.4: Harvest system productivity rates for practical application of HSA model example simulation

System	Productivity (tons/PMH)
Manual Felling Cable Skidding	12.2
Mechanized Felling Grapple Skidding	23.4
Shovel Bunching Grapple Skidding	17.7
Harvester Forwarder	22.1

The mechanized harvesting system has the highest production rate (Table 7.4), which is marginally higher than the production rate for the cut-to-length system. The utilization for the mechanized system was higher than that for the cut-to-length system resulting in the difference in productivity between the two systems being 2.9 tons per SMH.

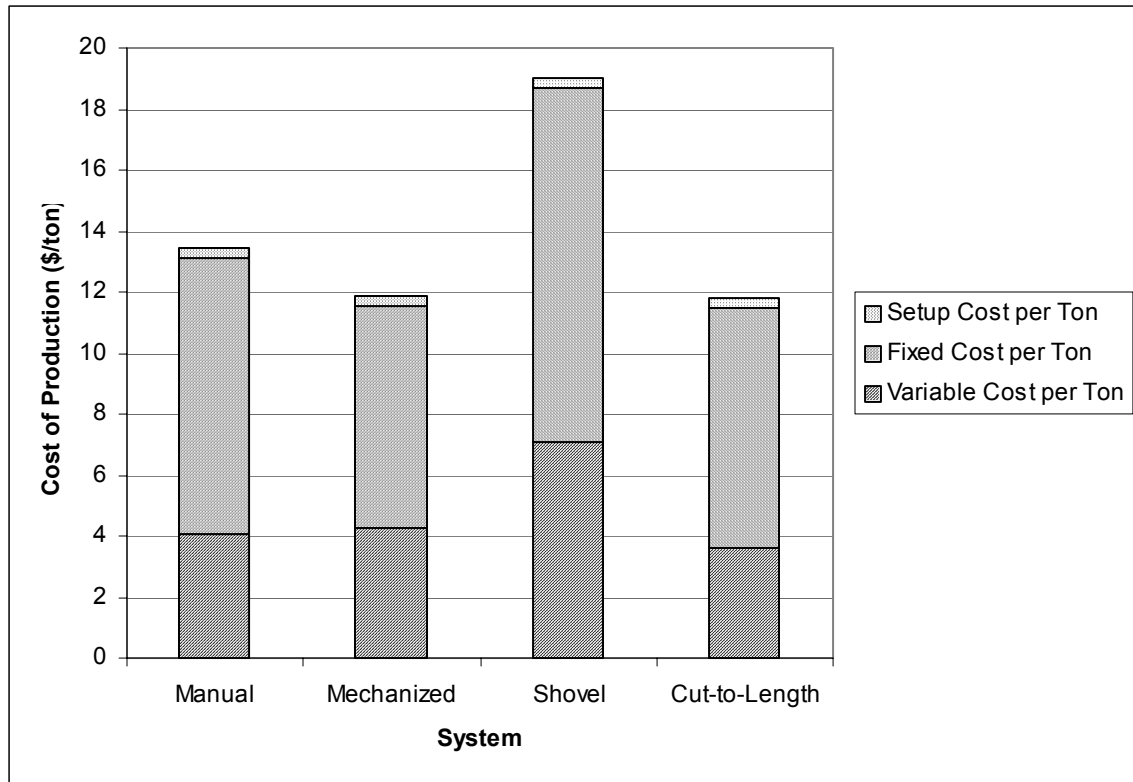


Figure 7.9: System harvesting costs per ton for practical application of HSA model example simulation

From Figure 7.9, the shovel system and manual system have a very high unit cost relative to the other two systems and should immediately be rejected from this analysis. The mechanized and cut-to-length systems are the most cost effective. The cut-to-length system has a slightly lower cost however the margin of the difference is very small. Because of the narrow margin between cost per unit for the mechanized and cut-to-length systems, no one system has a significant advantage over the other in terms of cost efficiency.

Presently, the decision between systems is clouded because of a relatively equal cost per unit. The mechanized system is higher productivity so more production is expected from this system even if the system suffers severe delays thus the mechanized system probably is more desirable based on the information presented so far.

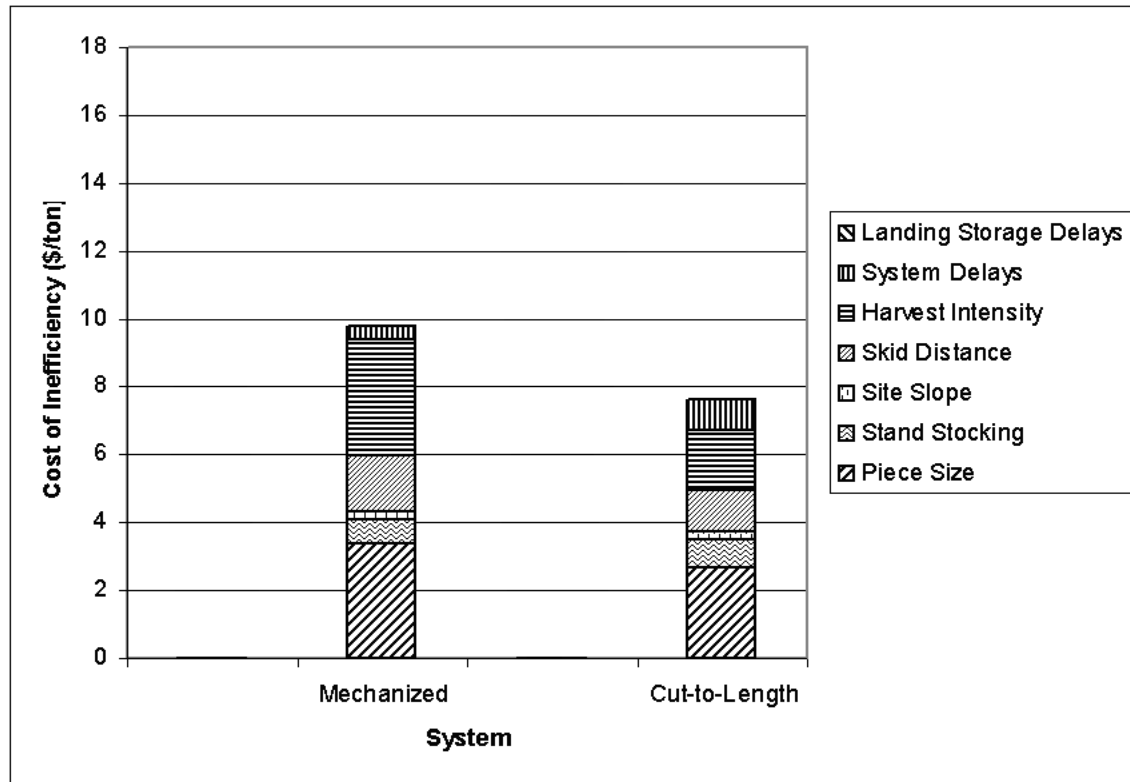


Figure 7.10: Harvest system cost of inefficiency ton for practical application of HSA model example simulation

It can be discerned from Figure 7.10, which parameters are most limiting to production and thus how sensitive a system is to uncertainty for a particular parameter, though sensitivity analysis is needed to provide a clearer understanding. What is of note in Figure 7.10 is the relative size of the Cost of Inefficiency of the mechanized system when compared to the Cost of Inefficiency for the cut-to-length system. The Cost of Inefficiency for the mechanized system is noticeably greater than for the cut-to-length system.

The production and cost efficiency output from the HSA model confirms that the cut-to-length system is twice as efficient (34 percent versus 17 percent) as the mechanized system. The mechanized system is severely limited on this particular site however the intrinsically relatively high production rate of mechanized systems clouds this fact. Because the mechanized system is so severely limited it is near a minimum point on the conceptual productivity curve. At the minimum point on the productivity curve the system has little flexibility and in the event of unexpected severe limitations

would suffer more than if it was away from the minimum. The cut-to-length system by contrast, is much less limited and has some flexibility, relative to the mechanized system, so is more able to cope with any unexpected severe limitations. Cut-to-length is the most appropriate system assignment decision for this particular stand.

7.2. MA Model

The purpose of this analysis of the MA model is to demonstrate the utility of the MA model in assessing machine allocation combinations and for providing feedback to assist the user in making informed changes to the machine allocation to improve the system as a whole.

There are three analyses that were conducted on the MA model:

1. Unbalanced system
2. Machine substitution
3. Skidder assignment regimes

7.2.1. Unbalanced system

The example unbalanced system is set up with an overcapacity of machines (five machines initially) in one phase, and one machine in each of the other two phases. A series of simulations are used to develop changes in the machine allocations to improve capacity utilization. A series of tables that approximate the calculations in the MA model describe the machine allocation decision process. The production estimates that are obtained in the tables in this section accurately represent the actual production estimates from the MA model.

Table 7.5: Initial distance of fellers from the landing

Feller	Initial Distance
1	100
2	200
3	300
4	400
5	500

Each felling machine begins at its initial distance (Table 7.5) and moves away from the landing to a maximum skid distance of 1500 feet from the landing and then returns to the landing (skid distance of zero) and begins moving away again.

When a felling machine has a felled inventory (felled by that machine) of 100 tons waiting to be skidded the feller enters a blockage state. When the felled inventory for a particular skidder is below 100 tons then the feller can continue felling.

The skid distances are based upon the start of a feller inventory. A skidder can only draw inventory from the current start point of a felled inventory. The skidders are all assigned to the largest felled inventory that exists when each skidder departs the landing.

A skidder enters a blockage state when the skidded inventory for that particular skidder reaches 15 tons. The value of 15 tons was chosen to represent a maximum inventory that would be placed waiting for processing. A skidder enters a starvation state if it arrives at a felled inventory and there is 0 tons in the inventory. This event could happen if all felled inventories are low, and one skidder is assigned to the largest inventory moments after another skidder has also been assigned to that inventory. The first skidder may remove all the timber at the inventory (if it is very low) and the second arriving skidder will enter a starvation state.

Table 7.6: Initialize time for skidders (seconds)

Skidder	Initialize-Time
1	500
2	1000
3	1500
4	2000
5	2500

The initialize time (Table 7.6) is used to create space between skidders and reduce the incidence of congestion delays. If all skidders were initialized at the same time, and

all went to the same inventory then they would experience a significant proportion of congestion delay at the acquisition point. The initialize time spreads the skidders out reducing the incidence of such congestions resulting in more efficient production.

The processors are all assigned to the largest skidded inventory and because processors are the last step in the production chain and so do not experience blockages.

For all machines in the system at the start and any machines added to the system:

- The felling machines are all feller-bunchers
- The skidders are all grapple skidders
- The processing machines are all processing machines.

Unbalanced System: Overcapacity of skidders

The system is set up initially with one feller, five skidders and one processor.

The initial system was modeled in the MA model and a series of reallocations of machinery made to the system, based upon the results from the MA model, to improve the system capacity utilization. One machine reallocation decision was made in each run of the MA model until a machine combination that represented the highest average capacity utilization was achieved.

Step 1

Table 7.7: Productivity of machines in Step 1 (initial system machine allocation combination)

Productivity (tons/SMH)	Felling	Skidding	Processing
1	14.9	3	11.7
2		2.5	
3		2.6	
4		2.6	
5		2.3	
Productivity (tons/SMH)	14.9	13.0	11.7
	System Productivity	# Machines	Ave. Throughput per Machine
	11.7	7	1.7

Table 7.7 shows that the average throughput per machine is 1.7 tons per SMH. This does not show enough information to determine how well the system is performing at its current machine allocation or what could be done to improve the performance. The machine utilizations are needed to assess how much of the capacity is being utilized.

Table 7.8: Utilization of machines in Step 1 (initial system machine allocation combination)

Utilization (percent)	Felling	Skidding	Processing
1	29	10.3	73.8
2		8.7	
3		8.8	
4		8.9	
5		8	
Average	29.0	8.9	73.8

Table 7.8 shows that the skidders have a very low utilization, while the processor has a relatively high utilization. The phase with the highest utilization is the bottleneck in the system, thus for this machine combination the processing phase is the bottleneck. There are three machine allocation decisions that can be made for this system: a feller could be added, a skidder could be removed or a processor could be added. It is infeasible to remove a feller or a processor because there must be at least one machine in each phase of the system.

Table 7.9: Production potentials of machines in Step 1 (initial machine allocation combination)

Production Potential	Felling	Skidding	Processing
1	51.4	29.1	15.9
2		28.7	
3		29.5	
4		29.2	
5		28.8	
Average	51.4	29.1	15.9

Using the production potentials (Table 7.9) the machine allocation decisions can be evaluated for the approach that will result in the highest average capacity utilization.

Adding a feller is not a feasible option to improve capacity utilization because felling is not the bottleneck phase. A machine should only be added to a particular phase if that phase is the bottleneck in the system.

Table 7.10: Estimated effect of removing a skidder in Step 2

Production Potential	Felling	Skidding	Processing
1	51.4	29.1	15.9
2		28.7	
3		29.5	
4		29.2	
5			
Total	51.4	116.6	15.9
Productivity at Utilization of 70 percent	36.0	81.6	11.1
Throughput per Machine	6.0	13.6	1.8

The average throughput per machine that is estimated for a machine combination is the throughput from the phase with the lowest throughput per machine. In Table 7.10 the result of this machine reallocation is that the average throughput per machine will be 1.8 tons per SMH. Processing will still be the bottleneck and the system will still have the

same productivity, however with one fewer machine in the system the average throughput per machine will increase.

Table 7.11: Estimated effect of adding a processor in Step 2

Production Potential	Felling	Skidding	Processing
1	51.4	29.1	15.9
2		28.7	15.9
3		29.5	
4		29.2	
5		28.8	
Total	51.4	145.4	31.8
Productivity at Utilization of 70 percent	36.0	101.8	22.2
Throughput per Machine	4.5	12.7	2.8

If a processor were added to the initial system machine combination in Step 2 then the predicted productivity is 2.8 tons per SMH per machine. This is much greater than the 1.8 predicted in Table 7.10 for the removal of a skidder. The preferred machine allocation decision is to add a processor.

The MA model output suggests a processor should be added and that the predicted productivity will be 2.8 tons per SMH.

Step 2

Table 7.12: Productivity of machines in Step 2

Productivity (tons/SMH)	Felling	Skidding	Processing	
1	26.1	5.1	11.6	
2		5.3	11.4	
3		4.1		
4		4.6		
5		5.1		
Productivity (tons/SMH)	26.1	24.2	23.0	
	System Productivity	# Machines	Ave. Throughput per Machine	Predicted Throughput per Machine
	23.0	8	2.9	2.8

The actual throughput per machine was 2.9 tons per SMH, slightly higher than the 2.8 tons per SMH predicted (Table 7.11).

Table 7.13: Utilization of machines in Step 2

Utilization (percent)	Felling	Skidding	Processing
1	50.8	16.5	72.8
2		16.9	71.5
3		13.1	
4		14.6	
5		16.1	
Average	50.8	15.4	72.2

The processing phase is identified as the bottleneck in the system because the processing machines have the highest utilization (Table 7.13). To improve average throughput per machine, either a skidder must be removed or a processor must be added.

Table 7.14: Production potentials for machines in Step 2

Production Potential	Felling	Skidding	Processing
1	51.4	30.9	15.9
2		31.4	15.9
3		31.3	
4		31.5	
5		31.7	
Average	51.4	31.4	15.9

The production potentials for the machines are shown in Table 7.14. In estimating the effect of machine allocation changes, the machine with the lowest utilization is removed from the phase that has an overcapacity, and the machine added to the bottleneck phase is assumed to have a production potential equal to the average of the production potentials for machines already in that phase.

Table 7.15: Effect of removing a skidder in Step 3

Production Potential	Felling	Skidding	Processing
1	51.4	30.9	15.9
2		31.4	15.9
3			
4		31.5	
5		31.7	
Total	51.4	125.5	31.9
Productivity at Utilization of 70 percent	36.0	87.8	22.3
Throughput per Machine	5.1	12.5	3.2

Skidder 3 would be the candidate for removal from the system in Step 3 because in Step 2 it had the lowest utilization of all the skidders (Table 7.13). As a result of removing this skidder it is estimated that the system would have an average throughput per machine of 3.2 tons per SMH (Table 7.15).

Table 7.16: Effect of adding a processor in Step 3

Production Potential	Felling	Skidding	Processing
1	51.4	30.9	15.9
2		31.4	15.9
3		31.3	15.9
4		31.5	
5		31.7	
Total	51.4	156.8	47.8
Productivity at Utilization of 70 percent	36.0	109.7	33.4
Throughput per Machine	4.0	12.2	3.7

The average throughput per machine is estimated to be 3.7 tons per SMH when a processor is added to the system (Table 7.16). The system will have a higher capacity utilization if a processor is added than if a skidder is removed from the system.

Step 3

Table 7.17: Productivity of machines in Step 3

Productivity (tons/SMH)	Felling	Skidding	Processing	
1	30.8	6.7	10.3	
2		6	9.3	
3		5.6	9.1	
4		6.2		
5		6		
Productivity (tons/SMH)	30.8	30.5	28.7	
	System Productivity	# Machines	Ave. Throughput per Machine	Predicted Throughput per Machine
	28.7	9	3.2	3.7

The addition of a processor increased the average throughput per machine to 3.2 tons per SMH (Table 7.17), 0.5 tons per SMH lower than predicted by the MA model (Table 7.16).

Table 7.18: Utilization of machines in Step 3

Utilization (percent)	Felling	Skidding	Processing
1	60	21.4	64.9
2		19.4	58.7
3		17.9	57.1
4		20.9	
5		19.3	
Average	60.0	19.8	60.2

The lower than expected throughput per machine was caused by the processing phase having a lower than anticipated utilization. The calculation in Table 7.16 that explains how the MA model predicted the productivity in Step 3 assumed a utilization of 70 percent. However, in Step 3 the utilization of the processing machines (the bottleneck phase) was only 60 percent. The machine reallocation in Step 3 did result in an increase in capacity utilization for the machines and the increase in capacity utilization was higher than had the machine allocation decision been to remove a skidder.

Table 7.19: Production potential of machines in Step 3

Production Potential	Felling	Skidding	Processing
1	51.3	31.3	15.9
2		30.9	15.8
3		31.3	15.9
4		29.7	
5		31.1	
Average	51.3	30.9	15.9

There are four options for machine allocation changes in Step 4. A feller can be added, a skidder can be removed, a processor can be added or a processor can be removed. Removing a processor would be to undo the previous machine allocation change that was made in Step 3 so would decrease the capacity utilization and is thus a redundant option and is discarded. From Table 7.18, the utilization of the felling and processing phases is the same, it is difficult to tell what the bottleneck is. Because of this ambiguity all three machine reallocation options should be evaluated.

Table 7.20: Add a feller in Step 4

Production Potential	Felling	Skidding	Processing
1	51.3	31.3	15.9
2	51.3	30.9	15.8
3		31.3	15.9
4		29.7	
5		31.1	
Total	102.6	154.3	47.7
Productivity at Utilization of 70 percent	71.8	108.0	33.4
Throughput per Machine	7.2	10.8	3.3

By adding a feller to the system in Step 4 it is predicted that the average throughput per machine will be 3.3 tons per SMH (Table 7.20), this represents an increase of 0.1 tons per SMH over the actual productivity in Step 3 (Table 7.17), and a decrease of 0.4 tons per SMH under the predicted productivity for Step 3 (Table 7.16).

Table 7.21: Effect of removing a skidder in Step 4

Production Potential	Felling	Skidding	Processing
1	51.3	31.3	15.9
2		30.9	15.8
3			15.9
4		29.7	
5		31.1	
Total	51.3	123.0	47.7
Productivity at Utilization of 70 percent	35.9	86.1	33.4
Throughput per Machine	4.5	10.8	4.2

The skidder with the lowest utilization (Table 7.18) is designated for removal. The removal of skidder 3 will not affect the productivity of the felling or skidding phases because there is a large overcapacity of skidders and the skidding capacity will not be reduced to a level where the felling stage will be blocked or the processing phase will be starved. As a result it is predicted that the system productivity will remain the same as in

Step 3 (Table 7.17), and the number of machines will be reduced by one. The predicted system productivity in Step 4 if a machine is added will be 4.2 tons per SMH per machine (Table 7.21).

Table 7.22: Effect of adding a processor in Step 4

Production Potential	Felling	Skidding	Processing
1	51.3	31.3	15.9
2		30.9	15.8
3		31.3	15.9
4		29.7	15.9
5		31.1	
Total	51.3	154.3	63.6
Productivity at Utilization of 70 percent	35.9	108.0	44.5
Throughput per Machine	3.6	10.8	4.4

Adding a processor in Step 4 is predicted to increase the average throughput per machine to 3.6 tons per SMH (Table 7.23). This is 0.4 tons per SMH higher than the actual average throughput per machine in Step 3, and 0.1 tons per SMH lower than the predicted average throughput per machine for Step 3 (Table 7.17). It is predicted (Table 7.22) that by adding a processor the felling phase will become the bottleneck that limits system throughput.

Based on the results in Tables 7.20, 7.21 and 7.22, the best machine allocation option in Step 4 is to remove a skidder.

Step 4

Table 7.23: Productivity of machines in Step 4

Productivity (tons/SMH)	Felling	Skidding	Processing	
1	34.1	8.6	10.6	
2		8.2	10.4	
3			11	
4		7.8		
5		8.4		
Productivity (tons/SMH)	34.1	33.0	32.0	
	System Productivity	# Machines	Ave. Throughput per Machine	Predicted Throughput per Machine
	32.0	8	4.0	4.2

The actual productivity in Step 4 (Table 17) was slightly lower than what was predicted in Table 15. The reason for this is that the utilization of the processing machines averaged 67 percent (Table 18), slightly lower than the 70 percent assumed in the calculation in Table 17. The processing phase is the bottleneck phase in the system, and if the utilization of this phase is more limited than predicted then the throughput of the processing phase and thus the system will suffer.

Table 7.24: Utilization of machines in Step 4

Utilization (percent)	Felling	Skidding	Processing
1	66.4	27.6	66.5
2		26	65.4
3			69.2
4		25.1	
5		27	
Average	66.4	26.4	67.0

Table 7.25: Production potential of machines in Step 4

Production Potential	Felling	Skidding	Processing
1	51.4	31.2	15.9
2		31.5	15.9
3			15.9
4		31.1	
5		31.1	
Average	51.4	31.2	15.9

There are five machine allocation decisions that can be made in Step 5. A feller can be added, a skidder added, a skidder removed, a processor added or a processor removed. One of these options can be discarded initially because it will undo decisions that have already been made. A skidder was removed in Step 4, it should not be added back in because it is known from Step 3 that this will decrease the average throughput per machine from Step 4.

Table 7.26: Effect of adding a feller in Step 5

Production Potential	Felling	Skidding	Processing
1	51.4	31.2	15.9
2	51.4	31.5	15.9
3			15.9
4		31.1	
5		31.1	
Total	102.8	124.9	47.7
Productivity at Utilization of 70 percent	71.9	87.4	33.4
Throughput per Machine	8.0	9.7	3.7

Adding a feller will balance the felling and skidding phases better, however the system is still limited by the processing phase which will cause the average system throughput to be 3.7 tons per SMH per machine (Table 7.26).

Table 7.27: Effect of removing a skidder in Step 5

Production Potential	Felling	Skidding	Processing
1	51.4	31.2	15.9
2		31.5	15.9
3			15.9
4			
5		31.1	
Total	51.4	93.8	47.7
Productivity at Utilization of 70 percent	35.9	65.7	33.4
Throughput per Machine	5.1	9.4	4.8

Removing a skidder will maintain system productivity at the same level as in Step 4 while reducing the number of machines causing the average throughput per machine to increase. Skidder 4 should be removed because it had the lowest utilization in Step 4.

Table 7.28: Effect of adding a processor in Step5

Production Potential	Felling	Skidding	Processing
1	51.4	31.2	15.9
2		31.5	15.9
3			15.9
4		31.1	15.9
5		31.1	
Total	51.4	124.9	63.6
Utilization of 70 percent	35.9	87.4	44.5
Throughput per Machine	4.0	9.7	4.9

The addition of a processor will increase the throughput of the system, however the full potential of the additional processor will not be realized because felling will become the bottleneck.

Table 7.29: Effect of removing a processor in Step 5

Production Potential	Felling	Skidding	Processing
1	51.4	31.2	15.9
2		31.5	
3			15.9
4		31.1	
5		31.1	
Total	51.4	124.9	31.8
Utilization of 70 percent	35.9	87.4	22.3
Throughput per Machine	5.1	12.5	3.2

The removal of a processor will reduce the number of machines but also the productivity of the system resulting in a decrease in average throughput per machine to 3.2 tons per SMH (Table 7.29).

Table 7.30: Machine allocation options in Step 5

Option	Average throughput per machine (tons/SMH)
Add feller	3.7
Remove skidder	4.8
Add processor	4.0
Remove processor	3.2

Table 7.30 is comprised of the predicted average throughput per machine from the machine allocations in Tables 7.26, 7.27, 7.28 and 7.29. The option that will result in the highest average throughput per machine is predicted to be removal the of a skidder which will increase average throughput per machine to 4.8 tons per SMH in Step 5 from the current level of 4.0 tons per SMH in Step 4.

Step 5

Table 7.31: Productivity of machines in Step 5

Productivity (tons/SMH)	Felling	Skidding	Processing	
1	34.7	11.5	10.6	
2		10.5	10.7	
3			11.2	
4				
5		11.3		
Productivity (tons/SMH)	34.7	33.3	32.5	
	System Productivity	# Machines	Ave. Throughput per Machine	Predicted Throughput per Machine
	32.5	7	4.6	4.8

The actual productivity in Step 5 was 4.6 tons per SMH per machine (Table 7.31), 0.2 tons per SMH per machine lower than the level that was predicted in Step 4 (Table 7.27).

Table 7.32: Utilization of machines in Step 5

Utilization (percent)	Felling	Skidding	Processing
1	67.5	39.1	66.3
2		35.8	67.4
3			70.5
4			
5		38.2	
Average	67.5	37.7	68.1

No changes were made to the felling and processing phases which are closely balanced, so these two phases remain as the bottlenecks in the system – processing had a higher utilization making it the most limiting phase.

Table 7.33: Production potential of machines in Step 5

Production Potential	Felling	Skidding	Processing
1	51.4	29.4	16.0
2		29.3	15.9
3			15.9
4			
5		29.6	
Average	51.4	29.4	15.9

There are five machine allocation options in Step 6 that are available: add feller, add skidder, remove skidder, add processor or remove processor. Because a skidder was removed in Step 5, to add a skidder in Step 6 is a redundant option and should be discarded immediately.

Table 7.34: Effect of adding a feller in Step 6

Production Potential	Felling	Skidding	Processing
1	51.4	29.4	16.0
2	51.4	29.3	15.9
3			15.9
4			
5		29.6	
Total	102.8	88.3	47.7
Productivity at Utilization of 70 percent	72.0	61.8	33.4
Throughput per Machine	9.0	7.7	4.2

Adding a feller will increase the productivity of the felling phase (Table 7.34) however, the processing phase will still be limiting to production so the full value of the additional feller will not be realized.

Table 7.35: Effect of removing a skidder in Step 6

Production Potential	Felling	Skidding	Processing
1	51.4	29.4	16.0
2			15.9
3			15.9
4			
5		29.6	
Total	51.4	59.0	47.7
Productivity at Utilization of 70 percent	36.0	41.3	33.4
Throughput per Machine	6.0	6.9	5.6

The removal of a skidder is estimated to result in average throughput per machine of 5.6 tons per SMH (Table 7.35), an increase of 1.0 tons per SMH from the productivity in Step 5. This occurs because the system productivity remains the same while the number of machines in the system will decrease by one. Skidder 2 should be removed because it had the lowest productivity of the skidding machines in Step 5.

Table 7.36: Effect of adding a processor in Step 6

Production Potential	Felling	Skidding	Processing
1	51.4	29.4	16.0
2		29.3	15.9
3			15.9
4			15.9
5		29.6	
Total	51.4	88.3	63.6
Productivity at Utilization of 70 percent	36.0	61.8	44.6
Throughput per Machine	4.5	7.7	5.6

The addition of a processor is estimated to result in a decrease in productivity of 0.1 tons per SMH per machine (Table 7.36).

Table 7.37: Effect of removing a processor in Step 6

Production Potential	Felling	Skidding	Processing
1	51.4	29.4	
2		29.3	15.9
3			15.9
4			
5		29.6	
Total	51.4	88.3	31.8
Productivity at Utilization of 70 percent	36.0	61.8	22.2
Throughput per Machine	6.0	10.3	3.7

Processor 1 should be removed because it had the lowest utilization of the processors in Step 5. Removing a processor is predicted to decrease the average throughput per machine to 3.7 tons per SMH (Table 7.37).

Table 7.38: Machine allocation options in Step 6

Option	Average throughput per machine (tons/SMH)
Add feller	4.2
Remove skidder	5.6
Add processor	4.5
Remove processor	3.7

Table 7.38 is a summary of the results from Tables 7.34, 7.35, 7.36 and 7.37, and shows that the best machine allocation decision in Step 6 is to remove a skidder from the system.

Step 6

Table 7.39: Productivity of machines in Step 6

Productivity (tons/SMH)	Felling	Skidding	Processing	
1	32.3	15.3	9.9	
2			9.9	
3			10.6	
4				
5		15.2		
Productivity (tons/SMH)	32.3	30.5	30.4	
	System Productivity	# Machines	Ave. Throughput per Machine	Predicted Throughput per Machine
	30.4	6	5.1	5.6

Table 7.40: Utilization of machines in Step 6

Utilization (percent)	Felling	Skidding	Processing
1	62.9	53.9	62.4
2			62
3			66.4
4			
5		53.7	
Average	62.9	53.8	63.6

Table 7.41: Production potential of machines in Step 6

Production Potential	Felling	Skidding	Processing
1	51.4	28.4	15.9
2			16.0
3			16.0
4			
5		28.3	
Average	51.4	28.3	15.9

The removal of a skidder in Step 6 resulted in an increase in average throughput per machine to 5.1 tons per SMH (Table 7.39). The actual productivity in Step 6 was 0.5 tons per SMH lower than the productivity that was predicted in Step 5 (Table 7.35). The

cause of this difference is that the utilization of the processing phase – the bottleneck phase was 63.6 percent in Step 6 while the prediction in Step 5 was based on a utilization of 70 percent.

There are five machine allocation decisions that can be made in Step 7: add feller, add skidder, remove skidder, add processor or remove processor. The option to add a skidder would undo the machine allocation made in Step 6 so this option is discarded immediately.

Table 7.42: Add feller in Step 7

Production Potential	Felling	Skidding	Processing
1	51.4	28.4	15.9
2	51.4		16.0
3			16.0
4			
5		28.3	
Total	102.8	56.7	47.8
Utilization of 70 percent	71.9	39.7	33.5
Throughput per Machine	10.3	5.7	4.8

The addition of a feller will result in a decrease in average throughput per machine because much of the additional capacity added by the feller will not be used as a result of blockages subsequent in the system caused by the low production of the processing phase. The resulting average throughput per machine will be 4.8 tons per SMH (Table 7.42), which represents a decrease of 0.3 tons per SMH from the average throughput per machine in Step 6 (Table 7.39).

Table 7.43: Remove skidder in Step 7

Production Potential	Felling	Skidding	Processing
1	51.4	28.4	15.9
2			16.0
3			16.0
4			
5			
Total	51.4	28.4	47.8
Productivity at Utilization of 70 percent	35.9	19.9	33.5
Throughput per Machine	7.2	4.0	6.7

Removal of a skidder will cause the skidding phase to become the bottleneck in the system and the average throughput per machine is predicted to drop to 4.0 tons per SMH (Table 7.43).

Table 7.44: Add processor in Step 7

Production Potential	Felling	Skidding	Processing
1	51.4	28.4	15.9
2			16.0
3			16.0
4			16.0
5		28.3	
Total	51.4	56.7	63.8
Productivity at Utilization of 70 percent	35.9	39.7	44.7
Throughput per Machine	5.1	5.7	6.4

The addition of a processor in Step 7 is predicted to result in a throughput per machine of 5.1 tons per SMH (Table 7.44).

Table 7.45: Remove processor in Step 7

Production Potential	Felling	Skidding	Processing
1	51.4	28.4	15.9
2			
3			16.0
4			
5		28.3	
Total	51.4	56.7	31.8
Productivity at Utilization of 70 percent	35.9	39.7	22.3
Throughput per Machine	7.2	7.9	4.5

Removing a processor is predicted to result in a decrease in average throughput per machine to 4.5 tons per SMH (Table 7.45).

Three of the machine allocation options for Step 7 are predicted to result in a decrease in productivity from that of Step 6 (Table 7.42, 7.43 and 7.45), the one option that is predicted to not decrease productivity is the addition of a processor (Table 7.44). It is predicted that the addition of a processor will result in the same average throughput per machine as in Step 6.

Step 7

Table 7.46: Productivity of machines in Step 7

Productivity (tons/SMH)	Felling	Skidding	Processing	
1	34.6	16.1	8.4	
2			8.4	
3			7.4	
4			8.3	
5		16.7		
Productivity (tons/SMH)	34.6	32.8	32.5	
	System Productivity	# Machines	Ave. Throughput per Machine	Predicted Throughput per Machine
	32.5	7	4.6	5.1

As a result of the machine allocation in Step 7 to add a processor the average throughput per machine decreased to 4.6 tons per SMH (Table 7.46). This occurred because the utilization of the machines (Table 7.47) was less than was assumed in the prediction calculation in Step 6 (Table 7.44).

Table 7.47: Utilization of machines in Step 7

Utilization (percent)	Felling	Skidding	Processing
1	67.3	57.4	53
2			52.7
3			46.5
4			52.1
5		59.5	
Average	67.3	58.5	51.1

All possible machine allocation decisions in Step 8 also resulted in decreased average throughput per machine from the machine combination in Step 6. The best machine combination to achieve the highest capacity utilization was achieved in Step 6: one feller, two skidders and three processors.

7.2.2. Machine substitution

Initial machine allocations were made using the balanced systems determined in section 7.2.1. From these balanced systems, machine types were substituted to determine any effect of machine substitution on machine interactions and productivity.

Machine substitution system 1

Table 7.48: Initial machine allocation for machine substitution system 1

Machine	Felling	Skidding	Processing
1	Feller-buncher	Grapple skidder	Processor
2		Grapple skidder	Processor
3			Processor
4			
5			

The feller-buncher was effectively substituted by two harvesters, or three motor manual chainsaw fellers. Substitution with harvesters results in a felling overcapacity of 10 tons per PMH. The processing capacity that is possessed by harvesters means that there is no need for processing machines in the system, this is an advantage that mitigates the effect of relatively low harvester productivity. Additionally, the harvesters add capacity to the skidders by reducing machine interactions between the skidders. Skidders have two inventories from which to draw, so there is less congestion delay from waiting and there is less starvation of the skidders.

Four chainsaw fellers are required to substitute one feller-buncher. The chainsaw fellers offer the same felling capacity and like the harvesters, also add capacity to the skidders by reducing skidder interactions at the stump.

Table 7.49: Alternative machine allocation for machine substitution system 1

Machine	Felling	Skidding	Processing
1	Motor-manual	Grapple skidder	Processor
2	Motor-manual	Grapple skidder	Processor
3	Motor-manual		Processor
4	Motor-manual		
5			

The three feller types offer different production capabilities and inherent characteristics. The production capabilities can be estimated using the MA model, however the inherent characteristics require expert knowledge by the user when modeling harvesting systems. The machine interaction output provided by the MA model provides important information as to how production capabilities of machines are limited and allows the user to infer possible solutions to improve the harvesting system.

Machine substitution system 2

Table 7.50: Initial machine allocation for machine substitution system 2

Machine	Felling	Skidding	Processing
1	Feller-buncher	Grapple skidder	Processor
2		Grapple skidder	Processor
3			Processor
4			
5			

Two grapple skidders can be replaced by four cable skidders. However this substitution is not easily made because the increase in number of skidders results in frequent congestion delays at the acquisition point. The congestion delays are very limiting to the individual productivity of the skidding machines and a significant proportion of production potential is lost. The skidding capacity of the four cable skidders in this example is 28 tons per PMH. In the absence of congestion delays these skidders would have a production of 50 tons per PMH.

The two grapple skidders can be replaced by two forwarders and maintain a balanced system. The forwarders experience a significant proportion of delay time. A forwarder has a much larger load capacity than a grapple skidder, as a result forwarders spend a large proportion of the cycle time accumulating a load at the stump. In the machine substitution system 2, the long load acquisition time meant that some congestion was experienced with every cycle when one forwarder was waiting for the other. The congestion effect could be mitigated if there were two felled inventories from which forwarders could draw loads.

Intuitively, the system requires rearrangement of phase sequence because generally forwarders transport processed material and in the system arrangement in this example the skidding machines were transporting unprocessed wood. Cable skidders are used as the example substitution in Table 7.51 because these machines are most appropriate for this type of system.

Table 7.51: Final machine allocation for machine substitution system 2

Machine	Felling	Skidding	Processing
1	Feller-buncher	Cable skidder	Processor
2		Cable skidder	Processor
3		Cable skidder	Processor
4		Cable skidder	
5			

Machine substitution system 3

Table 7.52: Initial machine allocation for machine substitution system 3

Machine	Felling	Skidding	Processing
1	Feller-buncher	Grapple skidder	Processor
2		Grapple skidder	Processor
3			Processor
4			
5			

The three processors in system 3 (Table 7.52) can be replaced by substituting four motor-manual chainsaws and maintain system balance. The chainsaws have a total processing capacity of 48 tons per PMH as compared to 50 tons per PMH for three processors. The alternative machine allocation for processing machines for the example system 3 is shown in Table 7.51.

Table 7.53: Final machine allocation for machine substitution system 3

Machine	Felling	Skidding	Processing
1	Feller-buncher	Grapple skidder	Motor-manual
2		Grapple skidder	Motor-manual
3			Motor-manual
4			Motor-manual
5			

7.2.3. Skidder Assignment

Table 7.54: Machine allocation for skidder assignment method evaluation

Machine	Felling	Skidding	Processing
1	Motor-Manual	Cable skidder	Motor-manual
2	Motor-Manual	Cable skidder	Motor-manual
3	Motor-Manual	Cable skidder	Motor-manual
4	Motor-Manual	Cable skidder	Motor-manual
5	Motor-manual	Cable skidder	Motor-manual

To evaluate the effectiveness of varying skidder assignment regimes a large manual harvest system was developed. The example system for evaluation of skidder assignment consists of manual felling, cable skidding and manual processing (Table 7.54). The purpose of having a high number of machines in the system is to provide many assignment possibilities and make full utilization of the skidder assignment methods for evaluation.

If skidders are too close together at an inventory and the inventory is not very large the first few skidders will deplete the inventory and following skidders will have small loads or be starved.

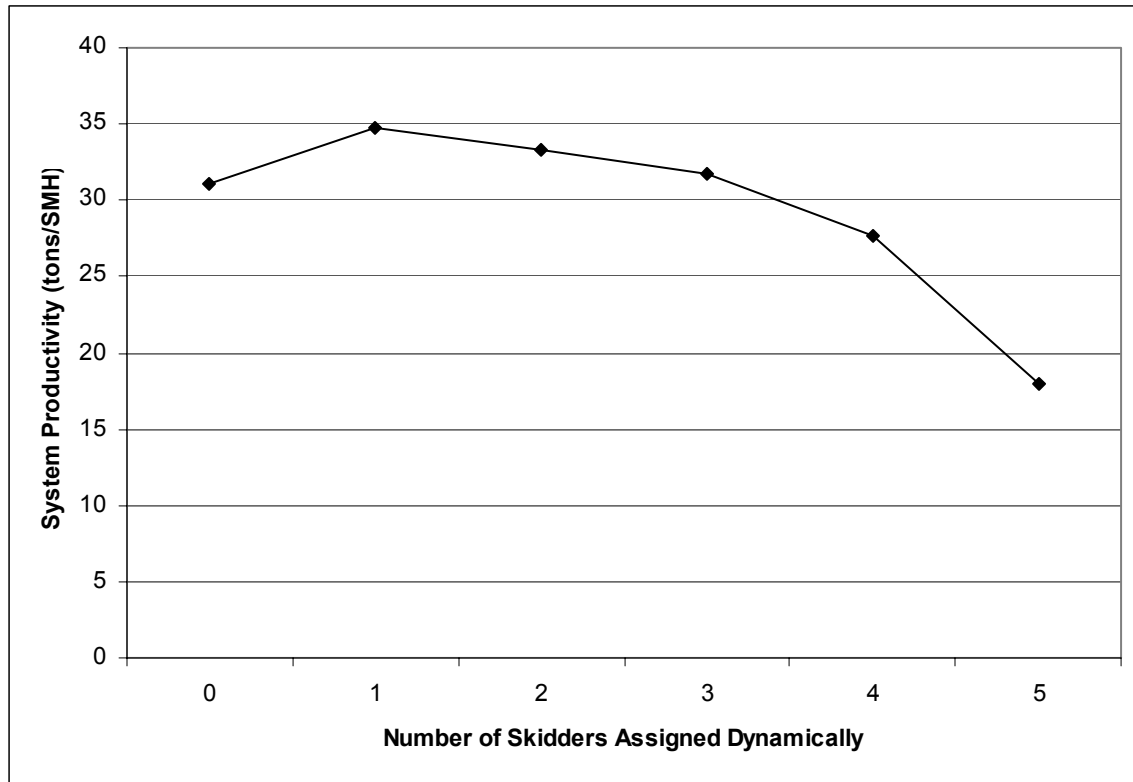


Figure 7.11: Effect of number of Dynamic-Fixed assignment methods on system productivity

The use of dynamic assignment methods such as largest inventory and inventory control can be beneficial to system productivity if incorporated in an appropriate manner. Figure 7.11 illustrates the effect of changing the assignment regime for skidders in the example system outlined in Table 7.54. With all skidders assigned in a Fixed manner (to different inventories) the productivity is high, however, some potential is lost through starvation and breakdowns. Changing the assignment method for one or two of the skidders to Largest Inventory results in an increase in the system productivity. The system productivity increases with the addition of two dynamic assignment regimes because the likelihood of a skidder sitting idle, when starved, decreases, and if a skidder breaks down and inventory is accumulating another skidder can draw from that inventory. The dynamic skidder assignment methods do not anticipate the future or make allowances for skidders already directed to a particular inventory. If a particular inventory is the largest, skidders will continue being directed to an inventory that already has a skidder in transit to it. In this way, more than one skidder can arrive at the same

inventory in a short time frame resulting in frequent, long congestion delays at the acquisition point. This behavior is demonstrated by the decline in system productivity associated with higher numbers of dynamic skidder assignments.

The dynamic assignment methods offer advantages but must be applied cautiously because of the severe congestions that can result.

7.2.4. Example of practical application of MA model

To examine the utility of the MA model an example application was performed. A logger owns 11 pieces of equipment as outlined in Table 7.55. The logger typically works in natural stands where piece size ranges between 12 and 22 inches, the tract layouts mean that skid distances range up to 1500 feet. A series of iterations of the MA model were run to determine the best machine allocation schedule.

Table 7.55: Example logger's harvesting machines to be allocated

Machine	Felling	Skidding	Processing
1	Feller-buncher	Grapple skidder	Processor
2	Motor-manual	Grapple skidder	Motor-manual
3	Motor-manual	Grapple skidder	Motor-manual
4		Cable skidder	Motor-manual
5			

A best allocation schedule was determined as a result of a series of simulations. The harvesting machines were allocated to two harvesting systems as outlined in Table 7.56 and 7.57. In all combinations of machinery that were examined, if there was more than one skidder in the system, one was assigned on a largest inventory basis, while the others were given fixed assignments.

Table 7.56: Mechanized harvesting system machine allocation

Machine	Felling	Skidding	Processing
1	Feller-buncher	Grapple skidder	Processor
2		Grapple skidder	Motor-manual
3			
4			
5			

Table 7.57: Manual harvesting system machine allocation

Machine	Felling	Skidding	Processing
1			
2	Motor-manual		
3	Motor-manual	Grapple skidder	Motor-manual
4		Cable skidder	Motor-manual
5			

The harvesting systems determined in Table 7.56 and 7.57 had the highest overall total machine utilization and productivity of all possible machine combinations. The mechanized system in Table 7.56 was well balanced, however, this made the system susceptible to starvation delays when the feller-buncher was in a breakdown delay state. There was only a small buffer inventory maintained between system phases and this inventory was quickly depleted when the machines feeding it entered a delay state. Skidder congestion delays were not a major source of delay time as may be expected with the two skidders drawing from only one inventory.

The manual system in Table 7.57 had a low felling capacity that resulted in frequent short starvation periods for the skidders and processors. This system could be improved by the addition of another feller. The accuracy of the skidding output could be questioned because there is no allowance in the acquisition state of grapple skidders for whether stems are bunched or scattered. Given that the manual system would have had scattered stems, because of the inability of the fellers to bunch, the productivity of the grapple skidder would probably be lower. However, the lower grapple skidder productivity would not be low enough offset the imbalance that exists between the felling, and the skidding and processing phases.

CHAPTER 8. SUMMARY AND CONCLUSIONS

Computer-based harvesting simulation models have existed since the late 1960s. Previous harvesting system simulations have focused on predicting the productivity of machines (Eliasson 1998, Eliasson and Lageson 1999, Greene *et al.* 1987, Block and Fridley 1990, Wang *et al.* 1998, Bragg *et al.* 1994) or whole harvesting systems (Randhawa and Olsen 1990, McDonald *et al.* 2001; Aedo-Ortiz *et al.* 1997; Wang and Greene 1999). STELLA systems dynamics simulation software was used to develop two computer-based harvesting system models.

8.1. Harvest System Assignment Model

The Harvest System Assignment (HSA) model is designed to assist users in making system-stand assignment decisions and to determine the impact of certain site and stand characteristics on system productivity. The HSA model is used to evaluate the performance of four general harvesting system types subject to terrain, tract and system constraints. Key site and stand parameters represent characteristics of the terrain and tract. The site and stand parameters limit system production rates, which are further limited by system constraints.

Site and stand data is then generated according to specified distributions and affects production rates through transformations by parameterized production functions. Each of the four harvesting system types has unique production functions which characterize how each system responds to particular parameters.

The HSA model provides output of the system productivity, efficiency and cost. The model also relates the limiting effect of site, stand and system parameters in terms of added cost of production. The simulation output is provided in a rapid manner detailing key comparative production figures that allow rapid ranking of systems and stands.

Incremental analyses using the HSA model showed some general traits of harvesting system performance, given the inputs used.

Manual systems are most sensitive to piece size. There is no maximum piece size limitation for manual systems, productivity is limited by small piece size. Other parameters such as slope do affect productivity of manual systems, however, to much less a degree than in the other three system types making manual systems very flexible in terms of stand assignment.

Mechanized systems have a maximum piece size that can be harvested, when exceeded the system productivity is reduced to 0 tons per PMH. The inherently high production potential of the mechanized harvesting systems causes these systems to have relatively low costs for most piece size values. Mechanized systems are most often limited by piece size, slope and are the most susceptible to landing storage delays.

Shovel systems have many similar behavioral traits to mechanized systems. Piece size, slope, skid distance, and often landing storage delays are typically limiting to shovel system performance. Shovel systems perform very poorly when the harvest intensity is a partial cut. The extra machine investment necessary in a shovel system typically results in higher costs.

Cut-to-length systems are most limited by site slope and to a lesser extent piece size. These systems perform comparatively well in sites of low harvest intensity and small piece size. Cut-to-length systems are generally high cost, however, in the right tract assignments can be a more effective solution and achieve higher productivity and lower cost than traditional system selections.

The precision of the HSA model allows a very detailed estimate of harvesting system effectiveness to be made.

The estimate of effectiveness of harvesting systems is only as accurate as the input values and transformations used in the model. Accuracy in the HSA model is gained by having good estimates of the site, stand and system parameter values, the production potential and the graphical functions used to calculate the effect on productivity of non-optimal parameters.

The HSA model will be employed as a training tool for industry. It will be used to educate loggers and managers about the impact of stand assignment decisions on the effectiveness of harvesting systems. Potentially, industry professionals could use the HSA model as a tool in an integrated harvest system assignment methodology.

8.1.1. Opportunities for further research

1. The graphical functions used in the HSA model to determine the effect on productivity are based on literature and designed to be applicable to a wide range of variations of a particular harvesting system type. To produce more accurate results, more research into harvesting system and machine productivity and limitations to productivity is needed, especially examining the cause and duration of delays.
2. There are many previous harvesting models. Much time and effort has been placed into developing these models and there is little literature detailing the use and advantage or otherwise of these models. Is there a cost-benefit that is realized and not recorded, or are many harvesting models simply an academic exercise with potential benefits that are never used by industry?

8.2. Machine Allocation Model

The Machine Allocation (MA) model is designed to allow users to evaluate the interaction of machinery in a system to assist machine allocation decisions. The MA model is used to simulate the activities of harvesting systems subject to key site and stand parameters. The site and stand parameters are used to define the activity and production of the machines.

The MA model can simulate a harvesting system based upon either of two general system layout options in the model that prioritize the occurrence of phases (felling, skidding and processing) in the harvesting system. Within each of the harvesting phases up to five machines can be specified from up to three machine type selections. The largest possible harvesting system can include up to 15 machines.

The productivity and delay output of the MA model gives insight into the balance among phases in the harvesting system and the effect of that balance on machine interactions.

Blockages at bottlenecks are often limiting to system production if inventories are managed at low levels. A machine enters a blocked state if the inventory to which it is delivering reaches or exceeds a maximum limit. Blockage delays are mitigated by

increasing the machines drawing from the inventory, substituting a lower productivity machine delivering to the inventory, substituting a higher productivity machine drawing from the inventory or increasing the inventory limit.

Breakdown delays are ever-present and reflect the intrinsic stoppages that occur for machines working in the woods. Breakdown delays decrease the productive time per schedule machine hour and thus also reduce the production per scheduled machine hour. The effect of breakdown delays can be mitigated by adding more machines to increase the production rate and by creating buffer inventories, which mitigate delays in subsequent phases of the harvesting system.

Starvation delays following bottlenecks are usually limiting to production if inventories are managed at low levels and during start up conditions where there is no buffer inventory to mitigate the effect of other delays, especially breakdowns, earlier in the production chain.

Congestion interactions, where the movement of one machine is restricted by another, are very severe limitations to harvesting systems with two or more skidders. The wait time involved in congestion delays can be in excess of 90 percent of scheduled operating time if a poor skidder assignment regime is used in an unbalanced system. Skidder assignment regimes are not treated with great depth in the MA model, rather the effect of skidder assignment is given attention.

There are four skidder assignment regimes available. The fixed and specified-order assignments generally result in few delays. If more than one skidder is assigned to one inventory, congestion delays can be mitigated by initializing the skidders at different times thereby separating the arrival of each skidder at the control points. If there are two or more skidders and largest inventory and inventory control assignments are used, delays can be reduced by allocating fixed assignment to one or more of the skidders.

The MA model is effective at analyzing system productivity and efficiency, and determining suitable machine allocation decisions. The level of precision exhibited by the MA model is high enough to warrant investigation of incorporating this methodology, using real-time information technology, into harvesting systems.

8.2.1. Opportunities for further research

1. The MA model is only an initial attempt to quantify a complex problem. Little is known about the frequency, duration and effects of machine interaction delays in forest harvesting systems. More field research is needed to be able to better predict the occurrence and effect of machine interaction delays.
2. While the MA model is comprehensive and meets the goals of this research it is limited by the nature of the STELLA software. STELLA is a continuous modeling environment that deals with rates, flows and accumulations. However, a similar model to the MA model could be produced in an object-oriented environment that may offer more utility for examination of machine interactions than that which has been accomplished in the MA model. An object-oriented environment or discrete-event simulation would offer the opportunity to record details of every delay and interaction in a way that is more suited to retrieval and analysis.
3. The methodology to analyze the potential effect of adding or removing a machine has been investigated with the MA model. The model accurately predicts the effect of a change in machine allocation. To gain benefits from this knowledge this methodology could be incorporated into the management of a pool of machinery. Real-time information from the machinery could be used to determine possible changes to make to improve the balance among machines.

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APPENDIX 1: HSA Production Functions

This section reports on the production functions used in the HSA model. The basic production functions gleaned from literature and used to synthesize generalized system production functions are listed in Appendix 1.

Function form

To support the structure of the HSA model the production functions used take on a proportionate rather than absolute form. The magnitude of the functions is determined based upon the production potential of the system.

The generalized system production functions were determined from production functions for typical machines used in each particular system. The deviation of the calculated production rate from each production function from the production rate at the maximum value was recorded as a percentage. This percentage deviation was then averaged for each production function for each machine in each system. The result is a series of points for each parameter that were combined into a function which describes the average effect of a parameter on the production potential for a particular harvesting system.

Sources of production functions:

Parameter	Manual	Mechanized	Shovel	Cut-to-Length
Piece Size	Lanford and Stokes 1996	Andersson 1992 Araki 1992 Gingras 1989 Araki 1994 Greene et al. 1987 Hartsough et al. 1997 Winsauer et al. 1984	Andersson 1997	Andersson 1992 Hartsough et al. 1997 McConchie and Evanson 1995 Richardson 1989 Andersson 1994 Richardson 1994
Stocking	Hassler et al. 2000 Lanford and Stokes 1996	Araki 1992 Greene et al. 1987 Winsauer et al. 1984	Andersson 1997	Eliasson 2000 Richardson 1989 Richardson 1994
Site Slope		Gingras 1989 Hartsough et al. 1997		Andersson 1997 Hartsough et al. 1997 Richardson 1989
Skid Distance	Hassler et al. 2000 Lanford and Stokes 1996	Klepac and Rummer 2000		Andersson 1992 Andersson 1994 Richardson 1994
Harvest Intensity	Hassler et al. 2000 Lanford and Stokes 1996	Greene et al. 1987 Winsauer et al. 1984		Eliasson 2000 Lageson 1997 Andersson 1994

Mechanized Harvesting System

Effect of Piece Size

$$\text{Percentage Change in Productivity} = (0.0832 * \text{DBH}^2) + (3.298 * \text{DBH}) - (99.154)$$

Effect of Stocking

$$\text{Percentage Change in Productivity} = (-3\text{E-}05 * \text{stocking}^2) + (0.0932 * \text{stocking}) - (80.635)$$

Effect of Slope

$$\text{Percentage Change in Productivity} = (-1.4274 * \text{slope}) + 0.3333$$

Effect of Harvest Intensity

$$\text{Percentage Change in Productivity} = (220.86 * \text{intensity}^3) - (410.66 * \text{intensity}^2) + (285.43 * \text{intensity}) - (92.538)$$

Effect of Skid Distance

$$\text{Percentage Change in Productivity} = (-6\text{E-}08 * \text{distance}^3) + (0.0002 * \text{distance}^2) - (0.2095 * \text{distance}) - (1.6306)$$

Manual Felling Cable Skidding Harvest System

Effect of Piece Size

$$\text{Percentage Change in Productivity} = (0.0755 * \text{DBH}^2) + (2.0765 * \text{DBH}) - (98.85)$$

Effect of Stocking

If stocking > 0

$$\text{Percentage Change in Productivity} = (-6\text{E}^{-06} * \text{stocking}^2) + (0.0156 * \text{stocking}) - (10.771)$$

If stocking = 0

$$\text{Percentage Change in Productivity} = -100$$

Effect of Harvest Intensity

If intensity > 0

$$\text{Percentage Change in Productivity} = (-37.5 * \text{intensity}^2) + (78.644 * \text{intensity}) - (42.117)$$

If intensity = 0

$$\text{Percentage Change in Productivity} = -100$$

Effect of Skid Distance

$$\text{Percentage Change in Productivity} = (-7\text{E}-08 * \text{distance}^3) + (0.0002 * \text{distance}^2) - (0.2216 * \text{distance}) + (14.807)$$

Figure xyz: Effect of skid distance on productivity of manual harvesting systems

Shovel Bunching/Forwarding Harvesting System

Effect of Piece Size

$$\text{Percentage Change in Productivity} = (0.0832 * \text{DBH}^2) + (3.298 * \text{DBH}) - (99.154)$$

Effect of Stocking

$$\text{Percentage Change in Productivity} = (-3\text{E-}05 * \text{stocking}^2) + (0.0932 * \text{stocking}) - (80.635)$$

Effect of Slope

$$\text{Percentage Change in Productivity} = (-1.4274 * \text{slope}) + 0.3333$$

Effect of Harvest Intensity

$$\text{Percentage Change in Productivity} = (220.86 * \text{intensity}^3) - (410.66 * \text{intensity}^2) + (285.43 * \text{intensity}) - (92.538)$$

Effect of Skid Distance

$$\text{Percentage Change in Productivity} = (-6\text{E-}08 * \text{distance}^3) + (0.0002 * \text{distance}^2) - (0.2095 * \text{distance}) - (1.6306)$$

Cut-to-Length Harvesting System

Effect of Piece Size

$$\text{Percentage Change in Productivity} = (-0.0167 * \text{DBH}^2) + (5.3766 * \text{DBH}) - (103.39)$$

Effect of Stocking

$$\text{Percentage Change in Productivity} = (7\text{E-}08 * \text{stocking}^3) - (0.0002 * \text{stocking}^2) + (0.1839 * \text{stocking}) - (82.698)$$

Effect of Slope

$$\text{Percentage Change in Productivity} = (4\text{E-}05 * \text{slope}^3) - (0.0055 * \text{slope}^2) - (1.0476 * \text{slope}) - (0.6061)$$

Effect of Harvest Intensity

If intensity > 0

$$\text{Percentage Change in Productivity} = (-34.47 * \text{intensity}^2) + (75.856 * \text{intensity}) - (42.25)$$

If intensity = 0

$$\text{Percentage Change in Productivity} = -100$$

Effect of Skid Distance

$$\text{Percentage Change in Productivity} = (-6\text{E-}08 * \text{distance}^3) + (0.0002 * \text{distance}^2) - (0.1873 * \text{distance}) + (12.088)$$

APPENDIX 2: MA PRODUCTION FUNCTIONS

The following is a list of sources of the production functions used in the MA model to define machine activity. Each production function is included in the MA model and the output of each is averaged to define machine activity.

Feller-buncher

Greene et al. 1987

Greene and McNeel 1987

Stokes and Lanford 1984

Harvester

Tufts and Brinker 1993 (81)

Tufts and Brinker 1983 (79)

Eliasson 2000

Eliasson et al. 1999

Glode 1999

Tufts 1997

Motor-manual chainsaw

Kluender and Stokes 1994

Kluender et al. 1998

Forwarder

Tufts and Brinker 1993 (79)

Tufts and Brinker 1993 (81)

Tufts 1997

Grapple Skidder

Kluender et al.1998

Greene and Stokes 1988

Klepac and Rummer 2000

Kluender et al. 1997

Tufts et al. 1988

Cable Skidder

Kluender et al. 1998

Processor

Evanson and McConchie 1996

Tufts and Brinker 1993 (79)

Motor-Manual Processing

Stokes and Lanford 1987

Kluender and Stokes 1994