A DECISION SUPPORT SYSTEM
FOR
MECHANIZED HARVESTING

by

Alan H. Steffert

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When considering a mechanized harvesting operation, the harvest planner or researcher is faced with a multitude of modern equipment choices. A decision support system (DSS) is presented to assist in selecting the appropriate level of mechanization. The DSS examines individual machines and formulates mechanized harvesting systems from them that adequately match the site and stand work environment, achieve user defined goals of a final product at a specific location, and operate within user defined constraints.

Individual machines are identified by assigned "attributes" describing the physical limits of operability and the equipment's interaction with other machines. Mechanized systems are constructed using the "output" of a machine (the product's state, location and accumulation arrangement) as an "input" for a successor machine. The "output-input" is also used as an eligibility requirement for potential successor machines in the system.

The DSS is implemented in a computer program called TIMBER HARVESTER for use on personal computers. The program makes use of a support data bases including mechanized equipment lists and common mechanized systems.

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INTRODUCTION

The nature of the timber resource in the Pacific North West region is changing. In recent times large scale harvesting has depleted the amount of old growth forest in the west, replacing the resource with new second growth regeneration and plantations characterized by generally uniform stands of smaller tree size. Environmental issues such as the Northern Spotted owl have highlighted the desire of the public to preserve the remnants of old growth forest and manage much of the remaining forested land (Federal, State and privately owned) for other values in addition to timber production. This increased environmental awareness has placed greater emphasis on the condition of the residual stand and on the possible long term site degradation due to logging operations. Consequently, much of the regions future wood fiber requirements will be met by the second growth forests, growing on a reduced land base with logging operated under strict controls.

The changing nature of the timber resource makes it all the more important to operate a logging operation efficiently and economically. The small size and uniformity of timber in the second growth stands lends itself to the use of mechanized harvesting equipment. This, coupled with the high cost of manual labor including worker compensation and insurance, is making the switch to mechanized harvesting equipment more attractive. Mechanized harvesting operations have a potential for high production rates and can often be double shifted in an attempt to use the equipment as economically as possible. Operators are protected from the dangers of the work environment and inclement weather by a cab.

Mechanized systems can impact the environment adversely. Operating a large piece of equipment on inappropriate ground can lead to adverse site degradation through compaction and rutting. It is very important that adverse impacts to the site be minimized through the correct choice of harvesting machines. The machines must also be capable of performing adequately in the type of stand in question and also be capable of efficient interaction with other machines making up the mechanized harvesting system.

Mechanized harvesting is utilized extensively in Scandinavia and in the some areas of North America. Many machines are currently available for use in the harvesting of timber. Machines can have single or multiple functions and be capable of producing many different products in widely differing terrain and stand conditions. Each machine has a unique range of stand and site conditions it can productively operate in without degrading the site. Each machine varies in its compatibility with other types of machines it can work with in a mechanized harvesting system. New technology is continuously expanding the operating ranges of these machines opening up more opportunities for the their application in the field. It is becoming increasingly difficult for harvest planners to assimilate all the types of harvesting equipment available today and choose the best combination for a particular logging operation. When preparing harvest plans for comparison, the analysis depends on the harvesting method selected by the users (Koger and Webster, 1986). With many land management agencies now using the interdisciplinary team approach to harvest planning, people unfamiliar with mechanized equipment are asked to judge the merit of one machine or system over another, often with little background in the subject.

LITERATURE REVIEW

Decision support systems (DSS) have been developed to help in the selection of mechanized harvesting systems. Mellgren (1978) presented guidelines for selecting mechanized systems from a choice of six currently in use. Each complete system was evaluated in terms of its economic performance in varying stand and terrain conditions and the results presented in a simple table. He suggests that slopes up to 30-35 percent are suitable for most mechanized systems and recommends that only systems using single function machines be considered above this limit.

The productive performance of harvesting machines operating individually and in systems was simulated by Stuart (1981) using the Harvesting Analysis Technique (HAT). HAT simulation has three parts. The stand is modeled, then individual machine performance, and finally the interaction of machines within the system. The effect of stand variables (stand density, tree volume etc.) on the systems production is investigated but not the site effects. It is assumed that the machines modeled are capable of operating on the terrain in question. The user defines the characteristics of the machines that make up the system. The output of one machine is the input for the next machine in the system and is described by the location, characteristics and form of material transferred.

Blinn and Sinclair (1986) also used HAT to simulate the effect of different stand parameters and product mixes on profitability for five existing harvesting systems. Other simulation packages such as LOGSIM (Randhawa and Olsen, 1990) also model productivity and machine interaction within mechanized harvesting systems. Empirical models such as the Auburn Harvesting Analyzer (Tufts et al. 1985) also provide production estimates for existing mechanized systems in varying stand conditions using production equations for each individual machine and by manual equipment balancing.

A relational data base software package, SPACE, was developed in Sweden to perform detailed and comprehensive harvesting system comparisons and select the most cost and revenue effective technology (Bjurulf and Tibblin, 1990). SPACE generates detailed stand data and the user inputs site data, prices and assortments of products required. Machines or systems to be analyzed are selected from a data base. SPACE is capable of investigating some of the most modern mechanized harvesting technology currently used in Scandinavia such as processors, harvesters, tree section combines and forwarders. This program is specific to forest conditions in Sweden and may not be suitable for transfer to USA.

A rule based expert system (ES) to recommend an appropriate timber harvesting system was developed by Gibson et al. (1986). The ES has the ability to take into account site and stand parameters as well as factors that may be hard to quantify such as concern for erosion or post harvest aesthetics. A limited number of specific harvesting systems are included in this ES and apply to limited geographical areas. A set of rules or knowledge base is used to compare the advantages and limitations of the individual components of the harvesting systems along with characteristics of other system components. The ES evaluates the feasibility of an entire harvesting system before making a recommendation. The ES concept can be expanded to include more systems by increasing the knowledge base. This requires more "experts" who are willing to express an opinion as an ES is only as good as the experts who devise the rule base.

Davis and Reisinger (1990) developed a DSS for planning large scale industrial timber harvest operations. A Geographic Information System (GIS) is utilized to combine terrain descriptions with machine operating capability. A descriptive terrain classification based on slope, ground firmness and surface roughness is assigned as an attribute for each polygon in the GIS. The descriptive classification is converted to a functional classification by considering the limiting operable terrain and the impacts on the site of three common mechanized harvesting systems. Systems that minimize the environmental damage and are economical are delineated in the GIS and a mixed integer programming analysis formulates the optimum system allocation. Although the DSS has the ability to investigate large areas utilizing GIS technology it is limited to decisions involving only the three harvesting systems.

Another large scale harvest planning tool is the Preliminary Logging Analysis System (PLANS). PLANS allows examination of a wide range of design and planning options for areas from one thousand to twenty five thousand acres using digital terrain modeling. Although mostly involving cable logging layout and road location, it is intended to add a physical and economic operability evaluation model for ground based equipment (McGaughey, 1991).

All the DSS to date analyze existing mechanized harvesting systems and little effort has been applied to generating other possible system alternatives. This approach is not very flexible for a DSS as the harvesting system to be evaluated is limited by the knowledge of the people defining the system rather than by what is physically possible on the site under investigation. Introduction of new machinery technology with the ability to operate on previously restricted areas such as steep slope or soft ground, and possibly carry out multiple functions expands the current frontiers of mechanized system operability.

A procedure that is able to evaluate the suitability of individual harvesting machines and generate feasible combinations of machines into harvesting systems is needed. This procedure must also have the ability to query users for any operating constraints and the products required. The harvesting alternatives and the data generated can then be evaluated for system capabilities using an established tool such as LOGSIM. As with all effective simulation or modeling, the critical consideration is identifying the system to be modeled (Randhawa et al. 1992). A DSS that has this ability will broaden the options available when considering possible mechanized systems for inclusion in future harvest plans.

OBJECTIVE STATEMENT

The objective of this Masters project is to develop a methodology for a decision support system that will enable feasible mechanized harvesting equipment alternatives to be generated by:

(1) Identifying and describing the factors that determine the eligibility of individual harvesting machines to operate, produce and interact with other equipment in forested terrain.

(2) Quantifying these factors for inclusion in a mechanized equipment database.

(3) Validating the application of the methodology in a computer program.

METHODOLOGY

A methodology has been developed for a DSS to enable the automatic generation of feasible mechanized harvesting systems. This methodology has three main objectives; the DSS must be capable of formulating mechanized harvesting systems from individual machines that:

(1) match the physical work environment.

* site
* stand

(2) achieve the users' goals i.e. produce a desired product from the stand:

* product state
* product location

(3) operate within user defined constraints, if any.

In addition the methodology for building the systems needs to be flexible. New machines or technology must be easily included.

The characteristics of the physical work environment that directly relate to a machine's operability need to be identified as well as those factors that influence the machines ability to produce. These will be used to ensure that (1) is satisfied. To achieve the users goals (2), combinations of machines need to be formed into systems. This will involve the interaction of machines. How do machines inter-relate?

A logical place to start when designing a methodology for the formulation of harvesting systems is to define what each machine can accept as an input form and subsequently transform into an output product. This approach has been used in simulations such as HAT (Stuart, 1981). Inputs and outputs of machines can be defined by three major characteristics:

(1) Product state: Describes the material form of the product at any point in the system.

(2) Product location: Defines the major locations within the harvesting work environment where product transformations occur.

(3) Product accumulation: Describes how the product is arranged with respect to itself.

These three characteristics define the "state" of the wood ie.: what it is, where it is and how it is arranged.

Product State

The definitions used are:

* Complete tree: The standing tree including roots and branches. This is the initial state from which all other products are ultimately derived.

* Whole tree: The severed tree bole including the branches.

* Tree length: The delimbed bole up to the merchantable top diameter.

* Log length: Sections of the delimbed bole after bucking.

* Shortwood: Short sections of delimbed tree bole, usually less than 10 feet long but could be as long as 20 feet.

* Chips: Wood chips.

Product Location

Defined as follows:

* Standing: The complete tree standing in the forest. This is always the starting point from which all other locations are subsequent.
* Stump: Right next to the stump. A location not accessible by vehicular machines except indirectly via an attachment, e.g. chokers.
* Skidtrail: Similar to the stump location but accessible to vehicular machines.
* Roadside: Next to a truck roadway.
* Landing: A standard landing with room to maneuver machinery.
* On Truck: Loaded on the back of a road transport vehicle.
* Concentration Yard: A central collection-sorting-storage area for several landings.

Product Accumulation

The three categories reflect the affect the arrangement can have on the operation of some machinery.

* Random: Located "randomly" or without predetermined direction. Usually refers to the complete tree standing in the forest.
* Single Piece in Lead: A product placed by a machine that has directional capability but not the ability to bunch several pieces.

* Bunched or Decked: Two or more pieces grouped together in a bunch, or if on a landing or roadside in a deck.

Having defined the input and output product states for each machine, mechanized harvesting systems can now be constructed. There are large numbers of harvesting machines now available that are capable of a wide range of tasks in the harvesting of timber. The range of machines and the tasks they are capable of will no doubt increase in the future. The possible combinations of all these machines into systems is potentially infinite. It soon becomes apparent that this would require a lot of search time during the formulation of systems if all machines had to be evaluated for input-output compatibility for each possible combination. To reduce the search time to manageable levels the use of a computer is mandatory. However even with modern computers the time required to evaluate all possible combinations is large.

The method devised to reduce the search time is to allocate each machine to an OPERATION. An operation can be thought of as a "loose" grouping of convenience for machines of similar function. An example would be the operation DELIMB defined as the removal of branches from the tree bole, be it at the stump, roadside or landing. After a machine has performed its task only machines allocated to the specified successor operations need to be considered for inclusion in the system for the further transformation of the product. By specifying the search for successor machines grouped by operations the computational time required to construct possible systems is reduced.

Operation Discussion

There are many basic tasks that are carried out in the woods to transform a complete tree into a desired product. These can be thought of as individual operations and are:
fell, bunch, top, delimb, buck (slash), skid, forward, load, haul, chip, debark, sort, pile, deck, hog, chunk, grind, crush, winch, split.

There are machines capable of doing these individual tasks as well as machines that can perform combinations of them. These multi task machines therefore perform a multi function operation. A multi function operation can be any combination of the tasks and is given an identifying name (see Table 1).

Table 1. Multi-Function Operations

OPERATION NAME*	INDIVIDUAL COMPONENTS
HARVEST:	fell -> bunch
	fell -> direct
	fell -> skid
	fell -> forward
	fell -> delimb
	fell -> delimb -> bunch
	fell -> delimb -> buck -> bunch
	fell -> delimb -> buck -> forward
PROCESS:	delimb -> buck
	delimb -> bunch
	buck -> bunch
	delimb -> buck -> bunch

(*) proposed ASAE standard names (Thompson, 1988)

IMPLEMENTING THE METHODOLOGY IN A DECISION SUPPORT SYSTEM

THE HARVESTING WORK ENVIRONMENT

Site Description

Davis and Reisinger (1990) discuss the classification of forested land for a DSS as either descriptive (resource based) or functional (machines operable based). A resource based site description is more appropriate for a DSS that allows for changes in machine technology as these very changes would make a functional description redundant.

Several authors (Mellgren, 1978; Radforth, 1978; Terlesk, 1983) have identified slope, surface roughness and ground bearing capacity as major limiting factors to machine off-road performance. In the past slope was the major factor in delineating between cable logged areas and ground based or tractor logged areas. Slope has a major effect on vehicle stability and travel speed. Technological advances have enabled more ground based equipment to be operated productively on steeper slopes. Classifying terrain for ground based logging based on slope alone is no longer as valid as it once was. Surface roughness and bearing capacity (firmness) of the soil further delineate the area for machinery usage. Roughness affects the travel speed of an off-road machine due to the machines maneuverability, its stability when operating and comfort for the operator. Roughness is a function of the size (height or depth) and the frequency of occurrence of obstacles (Silversides and Sundberg, 1989). A measure of roughness can also be used to determine a weave factor for vehicle (effective) speed. Ground firmness also affects productivity of machines and can be an indication of potential susceptibility of the ground to environmental damage.

A terrain classification system developed for the Canadian Pulp and Paper Association (CPPA) by Mellgren (1980) is the bases for the terrain classification used here. Ground firmness (Table 2) and ground roughness (Table 3) are divided into five classes which provide sufficient delineation without being too complicated for practical use. This system is used by the Forest Engineering Research Institute of Canada (FERIC) in its research and has already been applied to US forestry with local adjustment (Davis and Reisinger, 1990).

The classes (1-5) given for ground firmness are for normal summer conditions based on factors such as the soil texture and moisture levels. The Rated Machine Footprint Pressure is a measure of some off-road machinery characteristics (see Appendix IV) and has been related to the appropriate ground firmness class through field testing. For example, a man walking exerts a ground pressure underfoot in the order of 3-5 psi (20-35 kPa) and would require a minimum ground strength of class 4 to adequately support him.

The steepness of a site is defined by the average ground slope measured in percent. The sign of the slope indicates the haul direction for primary transport e.g. skidding. A positive slope is an adverse haul and a negative slope favorable. The average haul distance for primary transport of the product from the forest to the landing/roadside is required as a final site descriptor. This is determined using standard methods such as found in SAF Handbook, chapter 10.

Table 4 summarizes the physical variables used to describe the site.

Table 2. Ground Firmness (after Mellgren, 1980).

CLASS	1 VERY GOOD	2 GOOD	3 MODERATE	4 POOR	5 VERY POOR
SUMMER MOISTURE DESCRIPTION	VERY FREELY DRAINED	FREELY DRAINED	FRESH	MOIST WET	VERY WET
SOIL TEXTURE	COARSE SAND GRAVEL BEDROCK MATERIAL	MEDIUM COARSE SAND SANDY LOAMS	FINE SANDS SANDY SILT CLAY LOAMS	SILT CLAY ORGANIC SOIL (<2' DEEP)	ORGANIC SOILS (>2' DEEP)
RATED MACHINE FOOTPRINT PRESSURE(*)	30+ psi 200+ kPa	10-30 psi 70-200 kPa	6-10 psi 40-70 kPa	3-6 psi 20-40 kPa	0-3 psi 0-20 kPa

(*) see Appendix IV for calculation of Rated Machine Footprint Pressures

Table 3. Surface Roughness Criteria (after Mellgren, 1980).

	CLASS				
	1	2	3	4	5
OBSTACLE HEIGHT/ DEPTH	VERY EVEN	SLIGHTLY UNEVEN	UNEVEN	ROUGH	VERY ROUGH
4-12 in (10-30 cm)	0-4(*)	>4	>4	>4	>4
12-20 in (30-50 cm)	0	1-4	5-40	5-40	>40
20-28 in (50-70 cm)	0	0	1-4	1-4	>4
28-36 in (70-90 cm)	0	0	0	1-4	>4
>36 in (>90 cm)	0	0	0	0	>1

(*) Number of obstacles per 1076 ft^2 (100 m^2)

Table 4. Site Variable Summary

SITE VARIABLE	UNITS	RANGE OF MEASUREMENT
SLOPE	percent (+/-)	+50 (adverse) to -50 (favorable)
GROUND FIRMNESS	discrete scale	1(v.good) - 5(v.poor)
GROUND ROUGHNESS	discrete scale	1(v.even) - 5(v.rough)
AVERAGE HAUL DISTANCE	feet	0 +

Stand Description

The stand characteristics of the site are recorded from data taken from a standard preharvest inventory. The site is described by the following factors:

* Predominate merchantable species, selected from a data base of common species.

* Average diameter at breast height (dbh) in inches

* Average height of tree to merchantable top diameter in feet

* Average merchantable tree volume in cubic feet

* Stand density: (i) Number of merchantable trees per acre

  (ii) Number of unmerchantable trees per acre

* Stand area in acres

* Other user defined variables e.g. branchiness, brush factor etc

Stand variables were selected as important for their interaction with harvesting machinery. Review of literature highlighted the importance of these variables in the prediction of production rates and machine operability. Other stand variables are available from inventory data but a compromise between ease of use and model accuracy has reduced the variables used to the seven above.

User Constraints

The final component of the stand/site description is the operating constraints a user might place on the harvesting operation. Currently the two constraints considered are the use of non shear heads in the felling of standing timber and the requirement that both ends of the product be fully suspended during any transportation phase. Felling heads using shears have a history of damaging effects and subsequent reduction in quality of the butt log (McMorland, 1985), therefore non shear cutting heads may be required. Dragging a log with both ends on the ground is not only inefficient through increased skidding resistance but also more damaging to the ground (Conway 1982). Fully suspending logs during transportation results in a higher quality product devoid of dirt, mud, stone debris and drag damage delivered to a mill. Other constraints can be included indirectly. For example, if slash is required to be left in place out in the forest only machines that delimb and top in the woods would be included in the search for feasible systems.

HARVESTING EQUIPMENT DESCRIPTION

Each machine to be included in the DSS is described in a standard way to enable comparisons with the other harvesting equipment and the work environment. A set of descriptive machine attributes are used for determining a machines eligibility to operate on certain sites and/or for providing an indicator of potential performance on the site.

MACHINE ATTRIBUTE: Ground firmness

Mellgren (1980) introduces the idea of a standard rated footprint pressure, measured in a static situation with a standard "sinkage", to enable the comparison of off-road vehicles. The rating is designed to be used as an aid to selecting appropriate vehicles for operating on particular terrain. The rated foot print pressure for a machine is easily calculated (see Appendix IV) and is related to the ground firmness classes as shown in Table 2. The maximum ground firmness class a machine can operate on is read from the Table and assigned as a machine attribute.

MACHINE ATTRIBUTE: Ground Roughness

The ability of a machine to negotiate obstacles is a subjective measure that is hard to quantify. The roughness attribute assigned for each machine is based on factors such as a machine's minimum ground clearance, width, length, wheel base, agility (the ability to change direction radically and rapidly), turning circle, tractive effort available, center of gravity, function, undercarriage, etc. Silversides and Sundberg (1989) suggest that the minimum obstacle spacing required for many vehicles is 1.4 times the vehicles width. The frequency of obstacles of maximum size class is considered the limiting factor when evaluating an estimate of each machine's ability to productively operate on rough terrain. The maximum ground roughness a machine is able to be productively operated on is assigned as the machine roughness attribute.

Machines may have attachments or options that can change it's ability to negotiate obstacles. For example, bogey axles can reduce the vertical lift of a machine as it crosses an obstacle to half the obstacle height compared to the full height if crossed by a single axle vehicle.

A change in one component of a machine for whatever reason will usually affect some other machine function. Makkonen (1989) illustrates the subjective nature of the roughness measure well; "the choice of wider tires for better flotation may decrease the tractive effort that is available if the tire diameter is also increased. However, the tractive effort required may also be reduced because of the increased floatation and reduced rolling resistance. Also, wide tires require more steering force."

The maximum ground roughness class has been evaluated by field experience by Terlesk (1983) for individual primary transport machines and by Mellgren (1978) and Davis and Risinger (1990) for common mechanized systems.

MACHINE ATTRIBUTE: Slope

The maximum slope a machine can operate on in a favorable and adverse direction is recorded as a lower and upper bound. Side slope performance was not considered as it is assumed that a machine operating at the extremes of its range will be limited to working the parallel to the slope (the fall line). Non transporting (processing) machines will have the same upper and lower bounds. Primary transport machines generally have different upper and lower bounds. For example a rubber tired skidder may have an operating slope range with an upper bound of 20% due to the adverse slope and a lower bound of 40% when hauling down hill (favorable slope).

Machines confined in their operation to locations on road sides or landings are given the maximum rating (class 5) for both ground firmness and roughness. Similarly, they are assigned the maximum slope range. These locations are not representative of the site under investigation i.e. the woods, and assigning maximum values allows these machines to be considered for possible inclusion in harvesting systems for all site (but not all stand) conditions.

MACHINE ATTRIBUTE: Attachment

The attachment attribute describes the major attachment related to the operational effectiveness or productivity of the machine. This is used to further delineate between two otherwise similar machines. The attachment may be a grapple or cable for skidders, one grip or two grip processing heads for processors or harvesters, saw or shear for mechanized felling heads, etc. The choice of attachment can affect the machines eligibility for selection e.g. the saw vs shear head, or it may affect the operating performance e.g. cable vs grapple on a skidder.

MACHINE ATTRIBUTE: Horse Power (HP) Class

The horse power class is a descriptive term referring to the net horse power of the machine's main engine. Its main purpose is to identify the appropriate skidder speed table (see appendix I) for primary transport vehicles.

MACHINE ATTRIBUTE: Diameter

The diameter class defines the minimum and maximum diameter of tree that a machine can handle. This is an important attribute for machines that transform product state. A processor for example, has a maximum diameter of tree the delimbing arms can close around. The cable skidder on the other hand can attach itself to all diameters of product.

In some cases care must be taken when assigning the diameter attribute to a machine. Manufacturers specifications for stroke delimbers advise the maximum diameter of tree able to be delimbed by a certain machine. However, the actual maximum may be much less depending on the tree species and the height and taper of the trunk as the lifting power of the boom is often more critical than the diameter the delimbing knives can handle.

The diameter attribute is compared to the average dbh of the stand specified in the harvesting work environment. In most cases the tree dbh is assumed to be similar to the butt diameter for felling machines selection.

MACHINE ATTRIBUTE: Suspension

Machines that transport a product may have the ability to fully suspend both ends of the product. If so, the suspension attribute is defined as true. Machines that are not involved in the transport of the product are given the attribute true to ensure they are not excluded from the search.

MACHINE ATTRIBUTE: Regression Equations

The production rate of each machine in cunits (100 cubic feet) per productive machine hour (PMH) can be estimated in several ways. Regression equations use important site and stand variables to develop production rates that are unique to the machine in that particular situation. Alternatively, vehicle mechanics can be taken into account and a vehicles speed and load carrying ability for a given site can be specified and production calculated (see Appendix I).

The cunit is used as a measure of volume instead of the Pacific North West's more traditional unit, the board foot. This simplifies calculations of production when considering products as different as shortwood or tree lengths.

Regression equations were obtained from a wide range of published sources such as FERIC, CPPA, Logging Industry Research Association (LIRA), Oregon State University (OSU), Council on Forest Engineering (COFE), etc. (Kellogg et al. 1992). Examples of these are recorded with the appropriate machine in Appendix II.

MACHINE ATTRIBUTE: Owning and Operating Cost ($/PMH)

Each machine has a cost associated with owning and operating it. Standard costing guides for harvesting equipment are readily available (Brinker et al. 1989; Bushman and Olsen, 1988) and provide a step by step process for determining a machines cost per productive machine hour.

MACHINE ATTRIBUTE: Production Cost ($/cunit)

The production of the machine in cunits per PMH is combined with the cost of owning and operating the machine ($/PMH). The resulting factor is a production cost in dollars per cunit ($/cunit) of wood produced for the individual machine. The production cost of the mechanized system is the sum of all the individual machine costs.

The cumulative production cost of partially constructed systems is used as the directive force of the search algorithm utilized for selecting successor machines in the computerized version of the DSS (Scott 1991). The system production cost should not be used for any other purposes as the methodology does not take into account the effect of machine interactions within the harvesting system. However, the production cost estimates are useful when considering which systems to further analyze. Detailed system analysis using a simulation program such as LOGSIM is able to balance production rates and provide substantially more reliable system costs.

If suitable regression equations are unavailable for the machine operating in the particular environment, production costs must be estimated directly. Good contractors can often look at a job and formulate reasonable production estimates and knowing the cost of the machine, compute a cost per unit volume.

MACHINE ATTRIBUTES: Input-Output States (Product, Location, Accumulation) and Successor Operations

The attributes describing the input-output of the product for each machine are the most important for the construction of a feasible harvesting system. As previously discussed, these include the product, its location and accumulation state. For a given combination of input, there will be a certain output. The successor operation attribute lists the operations that can be carried out after the machine has finished its task, reducing the time and memory allocation during the search process. For example, a primary transport machine such as a cable skidder (see Table 5) can accept as input several product states at various locations and transports the product to a landing with no change to the product state. Regardless of the input accumulation, the output accumulation state is always bunched or decked. Successor operations listed are those that may be carried out after the current task is performed. Note that the search will not look at machines allocated to successor operations if the operation has previously been performed e.g. if the machines output product state was tree lengths (as opposed to whole trees) the successor operations delimb, top and process may not be considered. Machines of similar function are grouped together in an operation class. The attributes describing a machine give it a unique identity within that class. Table 6 summarizes the attributes required to adequately describe each machine.

Table 5. Input-Output states for a machine "cable skidder".

	INPUT	OUTPUT
PRODUCT STATE	whole tree ==> tree length ==>	whole tree tree length
PRODUCT LOCATION	stump ==> skidtrail ==>	landing landing
PRODUCT ACCUMULATION	random ==> single piece ==> bunched or decked ==>	bunched or decked bunched or decked bunched or decked
SUCCESSOR OPERATIONS	delimb buck top load process chip	

Table 6. Summary of Machine Attributes

OPERATION:	
MACHINE NAME:	
ATTACHMENT:	HP CLASS:
SUSPENSION: true / false	
SLOPE RANGE: ___ % (adverse)	___ % (favorable)
MAXIMUM GROUND ROUGHNESS: 1-5	MAXIMUM GROUND FIRMNESS: 1-5
TREE DIAMETER: MIN ___ in.	MAX ___ in.
COST ($/PMH):	COST ($/cunit):
INPUT-OUTPUT PRODUCTS:	PRODUCT STATE PRODUCT LOCATION PRODUCT ACCUMULATION
SUCCESSOR OPERATIONS:	
REGRESSION EQUATION:	

PUTTING IT ALL TOGETHER

Mechanized Equipment Data Base

A data base containing currently available mechanized harvesting equipment has been constructed for use with the DSS (see Appendix II). Certain common types of harvesting machines, e.g. skidders, are produced by more than one company. Often models from different manufacturers are almost identical in both form and function. To reduce duplication in the data base, similar individual machines are represented by a generic machine. The attributes describing each generic machine are based on an average of the attributes for individual machines that would make up that class. Like machines are allocated to a class based on such items as physical size, horsepower rating, load capacity, tree size capability, production rates, attachments, costs etc. When there are few machines of a particular type available, the individual machine is included in the data base with its own unique attributes.

Systems

Machines from the mechanized equipment data base have been grouped together to form various systems based on current systems commonly in use. These are named and stored in files for easy recall and matching to an environment. A mechanized harvesting system can be classified or named in many different ways. The loosest classification is the prominent operation e.g.: tractive (ground based) or cable logging. The DSS includes only ground based systems at this stage. The material form during primary transport is commonly used e.g.: tree length, whole tree or cut to length (log length or shortwood). Another classification method is to name the final product form e.g.: roundwood system, chipping system, integrated system. It is common with mechanized systems to name the major machines involved e.g.: fellerbuncher-grapple skidder system (Thompson, 1988).

Appendix III contains lists of the types of machines included in common mechanized harvesting systems.

The Methodology in Use: An Example

The following simple example illustrates the methodology used in the DSS for the formulation of alternative harvesting systems. Some (but not all) of the pertinent factors describing the site and stand for this example are: slope 0 % (flat ground), ground firmness class 1 (very good), ground roughness class 2 (slightly uneven) and average dbh of stand 16 inches. The product required from the woods is shortwood logs at a landing. User constraints require that no shear felling be allowed and all products be fully suspended off the ground when transported. An indirect user constraint is that all slash be left in the woods. This is accomplished by selecting a subset of machines from the mechanized equipment data base that are represented in cut to length mechanized systems (see Appendix II and III).

Machines are selected from three operations: Harvest, Process and Forward. For clarity, only the machine attributes directly relevant to the example are mentioned as full descriptions of each machine are included in Appendix II. The machines selected from the three operations for consideration are shown in table 7.

Table 7. Machines from cut to length systems considered in example.

OPERATION	MACHINE NAME	DESCRIPTION
Harvest	FB Level	feller buncher - leveling cab
	FB No Level	feller buncher - no leveling cab
	Single Grip Wheel	single grip wheeled harvester
	Track Leveling	leveling cab tracked harvester
Process	Single Grip	single grip in woods processor
	Double Grip	double grip in woods processor
Forward	Small Std(*)	small forwarder, standard tires
	Small Wide(*)	small forwarder, wide tires/bogies
	Large Std	large forwarder, standard tires
	Large Wide	large forwarder, wide tires/bogies

(*) These machines are selected as unavailable for the example.

The example list of typical mechanized equipment in cut to length systems contains ten machines. Not all these machines have to be included in the search for feasible harvesting systems. For example, there may be no small forwarder machines available for use in the region so the two small forwarders could be excluded from further consideration.

The remaining available machines are screened for compatibility with the harvesting work environment. All the machines are capable of working on the site but the Single Grip processor is excluded from further consideration as the maximum diameter tree it can handle (14 inches) is smaller than the average stand dbh of 16 inches. If any of the harvesting machines had a shear type felling head they would also be excluded at this stage.

The search for a feasible harvesting system starts with the operations Fell and Harvest. These are the only operations containing machines that can accept a standing tree (complete tree) as an input. The search algorithm looks for machines in each of these operations. The operation Fell contains no machines so the search in that direction is halted. Operation Harvest contains four machines: two feller bunchers (FB) and two harvesters. The FB's output products are whole trees bunched at a skidtrail. The successor operations for these machines are: Delimb, Buck, Top, Skid, Forward and Process. Only the operations Forward and Process have machines available for further consideration. The forwarders are checked for product input compatibility. Location and accumulation states of the FB's output is compatible with the input required by the forwarders but not the product state (whole trees). The search dead ends here and looks to the next successor operation, Process.

The Double Grip processor input requirements are compatible with the output of the FBs. The output product state of the processor is shortwood as required by the user but the location is at a skid trail, not a landing, so the search process continues. The successor operation of the Double Grip processor is Forward. Of the two forwarders available, both are compatible with the processor's output location and accumulation states and are capable of transporting shortwood logs. These machines are added to the system constructed so far. The output of the forwarders is shortwood bunched or decked at a landing. This is the product and location goal the user defined and the search along this branch is terminated.

An alternative search path starts with the two harvesters. Both machines produce shortwood product bunched at a skid trail. The user defined product state has been achieved but not the location. The successor operations to the harvesting machines is Forward. An input-output compatibility check of the two forwarders reveal that both machines are suitable, as in the system determined above. Their inclusion in the system produces the required product at the required location.

The example has treated several machines as one for the sake of clarity. The real search process looks at each machine individually and formulates partial systems simultaneously using the "best first" search algorithm.

A comprehensive search involving seven machines out of the original ten considered results in eight different combinations of machines (see Table 8). These alternative harvesting systems meet the user goals of matching the physical work environment, producing the required product at a specified location and operating within defined constraints. Alternative 1 is shown in more detail in Table 9., with the product state, location and accumulation shown at each stage in the system.

Table 8. Alternative harvesting systems generated by the DSS for producing shortwood length product at a landing.

1:	FB Level -> Double Grip -> Large Std
2:	FB No Level -> Double Grip -> Large Std
3:	FB Level -> Double Grip -> Large Wide
4:	FB No Level -> Double Grip -> Large Wide
5:	Single Grip Wheel -> Large Std
6:	Tracked Level -> Large Std
7:	Single Grip Wheel -> Large Wide
8:	Tracked Level -> Large Wide

Table 9. Detailed Description Output for Alternative 1.

OPERATION	MACHINE	PRODUCT	LOCATION	ACCUMULATION
(start)		complete tree	standing	random
HARVEST	FB Level	whole tree	skid trail	bunched
PROCESS	Double Grip	shortwood	skid trail	bunched
FORWARD	Large Std	shortwood	landing	bunched

The effect of changing one (or more) of the environmental descriptors is easily modeled. If the site became wetter and the ground firmness reduced from very good (class 1) to moderate (class 3), the forwarders with standard tires would be excluded from the search. The loss of these machines result in the DSS now generating four possible harvesting alternatives using six machines (see Table 10).

Table 10. Alternative harvesting systems generated by the DSS for producing shortwood length product at a landing on a site with ground firmness class 3.

3:	FB Level -> Double Grip -> Large Wide
4:	FB No Level -> Double Grip -> Large Wide
7:	Single Grip Wheel -> Large Wide
8:	Tracked Level -> Large Wide

If processing was not restricted to in the woods and alternative primary transport machinery, such as grapple skidders, were made available the possible combinations of machinery in the generated systems becomes much larger.

Application: The TIMBER HARVESTER Computer Program

The methodology described has been implemented in a series of computer programs known as TIMBER HARVESTER. TIMBER HARVESTER operates on IBM compatible personal computers running a 386 microprocessor, or better, with a math coprocessor and a mouse. Version 1 is written in SMALLTALK programming language and requires a copy of the SMALLTALK/V 286 program to operate (Scott 1991). TIMBER HARVESTER ver.2 is written in the C++ programming language and operates from a stand alone executable file. The latest version offers significant advances over the SMALLTALK version, including user friendliness through the use of direct on screen editing and window cycling.

Harvesting environments (site and stand parameters) and select groups of mechanized harvesting equipment are stored in separate data files. These can be created, retrieved or edited when using the TIMBER HARVESTER. The mechanized equipment files consist of sets of machines that are commonly found in existing mechanized systems. For example, a file representing common whole tree systems may contain many individual feller buncher type machines and many skidding machines (grapple, clambunk). These were selected from the equipment data base or entered directly when creating the file. Any machines included in the system file can be easily excluded from the search process if desired, for example, if they are not available in the users region.

DISCUSSION

Methodology

The methodology underlying the DSS for TIMBER HARVESTER is a simple and logical way of looking at how components of a mechanized harvesting system can go together. Using the output of one component as input to the next component of a system is a method common to some of the many DSS discussed in the literature review of this paper. The difference with this methodology is that the output of any machine is used as criteria to decide the eligibility of a possible successor machine and then passed on as input if the machine is suitable. The use of successor operations to speed up the search process when constructing systems is also a unique feature of TIMBER HARVESTER.

Initially the methodology included only single function operations. A multi function machine was allocated to several operations connected by the continuity of the output-input of the products. Although this idea works well within a system of predetermined machine combinations it proved unwieldy when applied to generating systems from scratch. The introduction of multi function operations enabled multi function machines to be included in the methodology with just the addition of two more operations (Harvest and Process). The result is a methodology for constructing mechanized harvesting systems that is flexible, logical and robust.

TIMBER HARVESTER Software Development

TIMBER HARVESTER was originally developed to operate as a model scenario generator for mechanized harvesting system simulation programs such as LOGSIM. As the project developed, interest was shown in a harvesting alternative generator that could in addition operate as a stand alone program for a variety of uses. This change in usage meant the program had to be upgraded to enable ease of operation by nontechnical users and compatibility with the majority of users' computers.

TIMBER HARVESTER Version 1.0 was written in an object orientated programming language, SMALLTALK, and the program was required to operate in a specific system environment. This allowed a user experienced in SMALLTALK to access the program source code and directly enter complicated predictive equations for machinery performance under varying conditions. In this manner, reasonably good production estimates could be automatically produced and updated as more and better information became available. Unfortunately SMALLTALK's operating environment is not widely used by many potential users of TIMBER HARVESTER.

To allow for widespread distribution the program needs to be accessed in a compiled form from executable files. For this reason another language was chosen. C++ is the current "hot" object orientated programming language and is compatible with other modern languages and programs for the inclusion of input-output data and subprograms (e.g. widow arrangement / mouse driver etc.). There is more scope for future program development and interaction with C++ than SMALLTALK.

Any major rewrite of software results in numerous "bugs" to be worked out. From the operational validation point of view, the debugging process involved running example system files for various products at different locations and closely examining the program results for logical inconsistencies. By working back through the system from the felling stage and increasing and adjusting different machinery combinations any problems within the search procedure could be isolated. As problems were identified they were communicated to the contract programmer for debugging. Several months of debugging has validated the search routine and produced a reasonably robust, easy to use program.

System Debugging

A similar procedure to that used for validating the search routine is also useful for identifying any errors a user may have when a run terminates in an unexpected result. This is often the case when a new machine is created by the user and does not appear as expected in the search for a new system. Often, the machine attributes were not entered as the user thought. The debug procedure involves making all machines contained in the system file unavailable for the search except for an initially small subset. This subset of available machines starts with a machine at the felling face (Fell or Harvest operation) and the system is added to one machine at a time to form a single chain. By making other machines available one by one and observing the result, the error (or inconsistency) involved in the attributes of the new machine can be identified.

Current Limitations of TIMBER HARVESTER

TIMBER HARVESTER version 2. is in many way superior to version 1. However, when validating the program with increasingly complex system test files the limitations of the program became apparent. A complex search for all the different combinations of mechanized equipment available today requires a lot of computer memory space. To generate any more than about 25 harvesting system scenarios requires an estimated one megabyte of RAM memory space. This is not expected to be a serious limitation to the program as the average user would be unlikely to generate this many scenarios when using subsets of the mechanized equipment data base contained in common system files.

The search routine used to generate the feasible systems in both versions, though extensive, is not exhaustive. The "best first" search relies on the cumulative production cost of the system constructed so far to indicate the direction of the search. Once the goal states are satisfied for a "branch", the search is complete. Other feasible systems with higher costs may not be identified. This problem can be overcome somewhat with adjustments to the machines available for the search. The cost of production ($/cunit) which takes into account production (cunits/PMH) on a particular site and machine cost ($/PMH), is an important user defined machine attribute in TIMBER HARVESTER ver. 2.

Very complex production regression equations for harvesting machines could be entered by the user directly in version 1 (Smalltalk language). Version 2 (C++ language) is only available in compiled form and the user cannot directly access the program code to enter production equation data. When upgrading to a compiled version, a compromise was made between including a user friendly production estimating capability with the limited time and computing expertise available to build this into the program. The ability to directly input complex production equations into compiled versions TIMBER HARVESTER will have to wait for future upgrades.

Future Improvements

The ability to create, edit or customize user defined production equations in a compiled version of TIMBER HARVESTER is desired. A process where the user selects a suitable equation form from a data base and gives values to the coefficients is possible and has been done in similar programs (Davis and Reisinger, 1990; Stuart, 1981). A data base of common regression equation forms can be put together easily by referencing a comprehensive document such as a compendium of mechanized harvesting research (Kellogg et al. 1992).

As the ability to make use of complex equations becomes available, there will be a need to more accurately describe the environment a machine will operate in. Some attributes describing the site and stand could be expanded. For example, the average stand dbh attribute could be enlarged to include a measure of the diameter distribution, as the maximum size of tree limits a machines use but the average dbh is more useful for production estimates. The present version has the space for three user defined "generic variables" that are available for use in production equations. This list will no doubt be added to in future versions.

Other additions to the program will be the expansion of the types of products produced. The present list of six states could be increased by including debarked product forms and different assortment breakdowns of the log length category.

The mechanized equipment data base will also need to be updated and added to as new equipment becomes available and old machines superseded. This will be an on going process as any computer program such as this is only as good as the data supplied to it.

CONCLUSION

Many tools are available to analyze mechanized harvesting systems. The majority of systems analyzed are those in common use and are assumed to be capable of operating in the given work environment. While analyzing existing systems is important for harvest planning, this reliance on established systems neglects the potential of different and emerging technology.

The methodology presented here and its application through the TIMBER HARVESTER program identifies mechanized harvesting systems that are feasible for specific work environments. TIMBER HARVESTER combines existing individual mechanized harvesting technology in a manner that takes into account a users product requirements, operating constraints and specifics of the site and stand when generating feasible mechanized systems. The scenarios generated can then be analyzed in greater depth by other existing procedures before inclusion in harvesting plans.

This program provides a much needed front end user interface for many mechanized harvest analyzers.

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APPENDICES

APPENDIX I

PRIMARY TRANSPORT SPEED AND LOAD TABLES

In many production equations or models for primary transport machines the load size is specified by the user. This variable is very important in determining the machine's production. The optimum load size can change depending on numerous factors relating to the work environment such as the haul distance or machine interaction etc. TIMBER HARVESTER uses a series of interactive tables for the major classes of skidders relating load sizes and travel speeds to operating slopes (see Table A1.). The tables are identified by horsepower class and attachment ie. cable or grapple. The table format allows the user to adjust the load size or speeds easily to reflect their specific conditions. Forwarders and clambunk skidders usually have an optimum load related to the size of the bunk and are assumed to operate at capacity therefore travel speed will be the main adjustment made to the table. The loads and speeds for each adverse slope class were derived from a chart published by the skidder manufacturer John Deere Ltd.(1983). The maximum combination of load and speed without exceeding the manufacturer's recommended loadings for standard tires is used. The soil was well drained, moderately firm forest soil and the load skidded is tree length boles (branches removed). Forwarder and clambunk speed and load data was obtained from manufacturer specifications. When on favorable hauls, the maximum speeds are reduced to safe working speeds as operators influence is often the overriding factor in the effective speed of off road vehicles rather than the vehicles mechanical potential (Radforth, 1978).

Radforth (1978) summarizes the factors affecting the speed of off road logging vehicles. He suggests that at any point on the terrain surface only one factor at a time, with the exception of slope, limits the travel speed of a vehicle. The effect of slope when superimposed on all the other problems is to amplify them. Adjustments to logging machinery production to account for the compounding effects of terrain conditions (eg. ground firmness and roughness) and product state for skidding and other operations has been calculated by Mellgren (1990). He uses a baseline production figure calculated from empirical data for many mechanized harvesting machines and adjusts this depending on the differences from the baseline environment and the actual environment. These adjustment factors can be accounted for in production estimates of some machines in the DSS by including relational and logical operators in the production equations. For example: IF product = whole tree AND ground firmness = class 3 THEN speed is reduced by 25%.

Table A1. Skidder Loads and Speeds. (adapted from John Deere Ltd. Skidder Selection Guide, 1983)

HP CLASS: <100
ATTACHMENT CLASS: CABLE

SLOPE (%)	LOAD (lb)	TRAVEL SPEED (mph) LOADED	EMPTY
-30	11000	10*	4.4
-20	11000	10*	5.9
-10	11000	10*	9.3
0	11000	4.9	12*
10	9000	3.7	12*
20	8000	2.5	12*
30	7000	2.2	12*

HP CLASS: <100
ATTACHMENT CLASS: GRAPPLE

SLOPE (%)	LOAD (lb)	TRAVEL SPEED (mph) LOADED	EMPTY
-30	8000	10*	3.9
-20	8000	10*	5.2
-10	8000	10*	8.1
0	8000	6.4	12*
10	6000	4.3	12*
20	5000	3.2	12*
30	4000	2.6	12*

HP CLASS: 100-140
ATTACHMENT CLASS: CABLE

SLOPE (%)	LOAD (lb)	TRAVEL SPEED (mph) LOADED	EMPTY
-30	11000	10*	4.2
-20	11000	10*	6.6
-10	11000	10*	8.9
0	11000	5.7	12*
10	9000	4.2	12*
20	8000	3.2	12*
30	7000	2.5	12*

HP CLASS: 100-140
ATTACHMENT CLASS: GRAPPLE

SLOPE (%)	LOAD (lb)	TRAVEL SPEED (mph) LOADED	EMPTY
-30	6000	10*	4
-20	6000	10*	4.9
-10	6000	10*	7.4
0	6000	8.3	12*
10	5000	5	12*
20	4000	4	12*
30	3000	3.2	12*

HP CLASS: >140
ATTACHMENT CLASS: CABLE

SLOPE (%)	LOAD (lb)	TRAVEL SPEED (mph) LOADED	EMPTY
-30	16000	10*	4.3
-20	16000	10*	5.4
-10	16000	10*	9.3
0	16000	5.8	12*
10	13000	4.3	12*
20	11000	3.3	12*
30	10000	2.5	12*

HP CLASS: >140
ATTACHMENT CLASS: GRAPPLE

SLOPE (%)	LOAD (lb)	TRAVEL SPEED (mph) LOADED	EMPTY
-30	11000	10*	3.6
-20	11000	10*	4.8
-10	11000	10*	7.2
0	11000	6.9	12*
10	9000	4.7	12*
20	8000	3.3	12*
30	7000	2.3	12*

(* Reduced to safe working speeds)

APPENDIX II

MECHANIZED EQUIPMENT DATA BASE

The following data base lists machines and their description (attributes) sorted by OPERATION.

OPERATION: HARVEST
MACHINE NAME: FB No Level
MACHINE DESCRIPTION NOTES: Swing boom feller buncher, eg. JD 693, CAT 227

ATTACHMENT:	saw	HP CLASS:	140
SUSPENSION:	true		
GROUND FIRMNESS (1-5):	3	GROUND ROUGHNESS (1-5):	4
MAXIMUM SLOPE FAVOURABLE (%):	-30	TREE DIAMETER MIN (in):	1
MAXIMUM SLOPE ADVERSE (%):	30	MAX (in):	20
UTILIZATION (%):	60		
COST ($/PMH):	128	PRODUCTION COST ($/cunit):	

	LOCATION INPUT	OUTPUT	PRODUCT INPUT	OUTPUT	ACCUMULATION INPUT	OUTPUT
1	standing	skidtrail	complete	whole tree	random	bunched
2						
3						
4						
5						

SUCCESSOR OPERATIONS: DELIMB, TOP, BUCK, SKID, FORWARD, PROCESS

REGRESSION EQUATION: see FERIC TR-84: Effect of Site and Stand Factors on Feller Buncher Performance.
Trees/PMH = 214.7-0.0054(stand density)-53.1(unmerch/merch)-10.7(ave DBH)+29.7(trees/cycle)

OPERATION: HARVEST
MACHINE NAME: FB Level
MACHINE DESCRIPTION NOTES: Cab leveling swing boom feller buncher, eg. Timbco 2518

ATTACHMENT:	saw	HP CLASS:	177
SUSPENSION:	true		
GROUND FIRMNESS (1-5):	3	GROUND ROUGHNESS (1-5):	4
MAXIMUM SLOPE FAVOURABLE (%):	-50	TREE DIAMETER MIN (in):	1
MAXIMUM SLOPE ADVERSE (%):	50	MAX (in):	20
UTILIZATION (%):	60		
COST ($/PMH):	141	PRODUCTION COST ($/cunit):	

	LOCATION INPUT	OUTPUT	PRODUCT INPUT	OUTPUT	ACCUMULATION INPUT	OUTPUT
1	standing	skidtrail	complete	whole tree	random	bunched
2						
3						
4						
5						

SUCCESSOR OPERATIONS: DELIMB, BUCK, TOP, SKID, FORWARD, PROCESS

REGRESSION EQUATION: see FERIC TR-84: Effect of Site and Stand Factors on Feller Buncher Performance.
Trees/PMH = 108.1+0.13(stand density)+14.3(trees/cycle)

OPERATION: HARVEST
MACHINE NAME: Track Leveling
MACHINE DESCRIPTION NOTES: Cab leveling, fell-delimb-buck harvester, eg. Valmet 500T.

ATTACHMENT:	saw	HP CLASS:	177
SUSPENSION:	true		
GROUND FIRMNESS (1-5):	3	GROUND ROUGHNESS (1-5):	4
MAXIMUM SLOPE FAVOURABLE (%):	-50	TREE DIAMETER MIN (in):	2
MAXIMUM SLOPE ADVERSE (%):	50	MAX (in):	20
UTILIZATION (%):	?		
COST ($/PMH):	?	PRODUCTION COST ($/cunit):	

	LOCATION INPUT	OUTPUT	PRODUCT INPUT	OUTPUT	ACCUMULATION INPUT	OUTPUT
1	standing	skidtrail	complete	log length	random	bunched
2			complete	shortwood		
3						
4						
5						

SUCCESSOR OPERATIONS: FORWARD

REGRESSION EQUATION: ND

OPERATION: HARVEST
MACHINE NAME: Single Grip wheeled
MACHINE DESCRIPTION NOTES: Single grip harvester on wheeled carrier, eg. FMG 990, Valmet 546H.

ATTACHMENT: saw/single grip — HP CLASS: 155
SUSPENSION: true
GROUND FIRMNESS (1-5): 3 — GROUND ROUGHNESS (1-5): 4
MAXIMUM SLOPE FAVOURABLE (%): -30 — TREE DIAMETER MIN (in): 2
MAXIMUM SLOPE ADVERSE (%): 30 — MAX (in): 20
UTILIZATION (%): 65
COST ($/PMH): 189 — PRODUCTION COST ($/cunit):

	LOCATION		PRODUCT		ACCUMULATION	
	INPUT	OUTPUT	INPUT	OUTPUT	INPUT	OUTPUT
1	standing	skidtrail	complete	log length	random	bunched
2			complete	short wood		
3						
4						
5						

SUCCESSOR OPERATIONS: FORWARD

REGRESSION EQUATION: ND

OPERATION: HARVEST
MACHINE NAME: Feller Skidder
MACHINE DESCRIPTION NOTES: Ranger Kockums Feller Skidder

ATTACHMENT: saw — HP CLASS: 206
SUSPENSION: false
GROUND FIRMNESS (1-5): 2 — GROUND ROUGHNESS (1-5): 4
MAXIMUM SLOPE FAVOURABLE (%): -25 — TREE DIAMETER MIN (in): 1
MAXIMUM SLOPE ADVERSE (%): 25 — MAX (in): 16
UTILIZATION (%): 74
COST ($/PMH): 233 — PRODUCTION COST ($/cunit):

	LOCATION		PRODUCT		ACCUMULATION	
	INPUT	OUTPUT	INPUT	OUTPUT	INPUT	OUTPUT
1	standing	landing	complete	whole tree	random	bunched
2						
3						
4						
5						

SUCCESSOR OPERATIONS: PROCESS, DELIMB, TOP

REGRESSION EQUATION: ND : see FERIC TN-117 for production figures

OPERATION: HARVEST
MACHINE NAME: Feller Forwarder
MACHINE DESCRIPTION NOTES: K2FF feller forwarder, payload 35000 lbs

ATTACHMENT: saw — HP CLASS: 150
SUSPENSION: true
GROUND FIRMNESS (1-5): 3 — GROUND ROUGHNESS (1-5): 4
MAXIMUM SLOPE FAVOURABLE (%): -35 — TREE DIAMETER MIN (in): 1
MAXIMUM SLOPE ADVERSE (%): 15 — MAX (in): 18
UTILIZATION (%): 60
COST ($/PMH): ? — PRODUCTION COST ($/cunit):

	LOCATION		PRODUCT		ACCUMULATION	
	INPUT	OUTPUT	INPUT	OUTPUT	INPUT	OUTPUT
1	standing	landing	complete	whole tree	random	bunched
2						
3						
4						
5						

SUCCESSOR OPERATIONS: PROCESS, DELIMB, TOP

REGRESSION EQUATION: ND

OPERATION: PROCESS
MACHINE NAME: Single Grip
MACHINE DESCRIPTION NOTES: Single grip processor on landing, eg. Styer KP60 on wheeled loader

ATTACHMENT: single grip | HP CLASS: 200
SUSPENSION: true
GROUND FIRMNESS (1-5): 5 | GROUND ROUGHNESS (1-5): 5
MAXIMUM SLOPE FAVOURABLE (%): -50 | TREE DIAMETER MIN (in): 5
MAXIMUM SLOPE ADVERSE (%): 50 | MAX (in): 23
UTILIZATION (%): 60
COST ($/PMH): 142 | PRODUCTION COST ($/cunit):

	LOCATION		PRODUCT		ACCUMULATION	
	INPUT	OUTPUT	INPUT	OUTPUT	INPUT	OUTPUT
1	landing	landing	whole tree	log length	bunched	bunched
2			whole tree	short wood		
3						
4						
5						

SUCCESSOR OPERATIONS: LOAD

REGRESSION EQUATION: ND

OPERATION: PROCESS
MACHINE NAME: Single Grip
MACHINE DESCRIPTION NOTES: Single grip head on tracked excavator, Delimb-buck in woods, eg KP 40.

ATTACHMENT: single grip | HP CLASS: 125
SUSPENSION: true
GROUND FIRMNESS (1-5): 3 | GROUND ROUGHNESS (1-5): 4
MAXIMUM SLOPE FAVOURABLE (%): -30 | TREE DIAMETER MIN (in): 2
MAXIMUM SLOPE ADVERSE (%): 30 | MAX (in): 14
UTILIZATION (%): 60
COST ($/PMH): 101 | PRODUCTION COST ($/cunit):

	LOCATION		PRODUCT		ACCUMULATION	
	INPUT	OUTPUT	INPUT	OUTPUT	INPUT	OUTPUT
1	stump	skidtrail	whole tree	log length	single piece	bunched
2	skidtrail	skidtrail	whole tree	shortwood	bunched	bunched
3						
4						
5						

SUCCESSOR OPERATIONS: FORWARD

REGRESSION EQUATION: ND

OPERATION: PROCESS
MACHINE NAME: Double Grip
MACHINE DESCRIPTION NOTES: Double grip, in woods processor, eg. Rotne Rapid 860.

ATTACHMENT: double grip | HP CLASS: 96
SUSPENSION: true
GROUND FIRMNESS (1-5): 3 | GROUND ROUGHNESS (1-5): 4
MAXIMUM SLOPE FAVOURABLE (%): -30 | TREE DIAMETER MIN (in): 2
MAXIMUM SLOPE ADVERSE (%): 30 | MAX (in): 20
UTILIZATION (%): ?
COST ($/PMH): ? | PRODUCTION COST ($/cunit):

	LOCATION		PRODUCT		ACCUMULATION	
	INPUT	OUTPUT	INPUT	OUTPUT	INPUT	OUTPUT
1	stump	skidtrail	whole tree	log length	single piece	bunched
2	skidtrail	skidtrail	whole tree	shortwood	bunched	bunched
3						
4						
5						

SUCCESSOR OPERATIONS: FORWARD

REGRESSION EQUATION: ND

OPERATION: PROCESS
MACHINE NAME: Stroke Deck
MACHINE DESCRIPTION NOTES: stroke deck processor, eg. Hahn 300F

ATTACHMENT: grapple
SUSPENSION: true
GROUND FIRMNESS (1-5): 5
MAXIMUM SLOPE FAVOURABLE (%): -50
MAXIMUM SLOPE ADVERSE (%): 50
UTILIZATION (%): 60
COST ($/PMH): 113
HP CLASS: 176
GROUND ROUGHNESS (1-5): 5
TREE DIAMETER MIN (in): 3
MAX (in): 32
PRODUCTION COST ($/cunit):

	LOCATION		PRODUCT		ACCUMULATION	
	INPUT	OUTPUT	INPUT	OUTPUT	INPUT	OUTPUT
1	landing	landing	whole tree	log length	bunched	bunched
2			whole tree	short wood		
3						
4						
5						

SUCCESSOR OPERATIONS: LOAD

REGRESSION EQUATION: ND

OPERATION: PROCESS
MACHINE NAME: Stroke Boom
MACHINE DESCRIPTION NOTES: Stroke boom delimber, tree length or log length, eg Denis DM 3000 on Cat 229

ATTACHMENT:
SUSPENSION: true
GROUND FIRMNESS (1-5): 5
MAXIMUM SLOPE FAVOURABLE (%): -50
MAXIMUM SLOPE ADVERSE (%): 50
UTILIZATION (%): 60
COST ($/PMH): 208
HP CLASS: 180
GROUND ROUGHNESS (1-5): 5
TREE DIAMETER MIN (in): 2
MAX (in): 22
PRODUCTION COST ($/cunit):

	LOCATION		PRODUCT		ACCUMULATION	
	INPUT	OUTPUT	INPUT	OUTPUT	INPUT	OUTPUT
1	landing	landing	whole tree	tree length	bunched	bunched
2	roadside	roadside	whole tree	log length		
3						
4						
5						

SUCCESSOR OPERATIONS: BUCK, LOAD

REGRESSION EQUATION: If tree vol<5.3 ft3 THEN 180 trees/PMH; If tree vol>5.3 ft^3 THEN 108 trees/PMH.

OPERATION: BUCK
MACHINE NAME: Slasher
MACHINE DESCRIPTION NOTES:

ATTACHMENT: saw
SUSPENSION: true
GROUND FIRMNESS (1-5): 5
MAXIMUM SLOPE FAVOURABLE (%): -50
MAXIMUM SLOPE ADVERSE (%): 50
UTILIZATION (%): 67
COST ($/PMH): 44
HP CLASS: ?
GROUND ROUGHNESS (1-5): 5
TREE DIAMETER MIN (in): 1
MAX (in): 40
PRODUCTION COST ($/cunit):

	LOCATION		PRODUCT		ACCUMULATION	
	INPUT	OUTPUT	INPUT	OUTPUT	INPUT	OUTPUT
1	landing	landing	tree length	shortwood	bunched	bunched
2			tree length	log length		
3						
4						
5						

SUCCESSOR OPERATIONS: LOAD

REGRESSION EQUATION: ND

OPERATION: SKID
MACHINE NAME: RTSchoSm
MACHINE DESCRIPTION NOTES: Rubber Tired Skidder - small class

ATTACHMENT: cable
HP CLASS: 90 (small)
SUSPENSION: false
GROUND FIRMNESS (1-5): 3
GROUND ROUGHNESS (1-5): 4
MAXIMUM SLOPE FAVOURABLE (%): -30
TREE DIAMETER MIN (in): 1
MAXIMUM SLOPE ADVERSE (%): 30
MAX (in): 40
UTILIZATION (%): 65
COST ($/PMH): 58
PRODUCTION COST ($/cunit):

	LOCATION		PRODUCT		ACCUMULATION	
	INPUT	OUTPUT	INPUT	OUTPUT	INPUT	OUTPUT
1	stump	landing	whole tree	whole tree	random	bunched
2	skidtrail	landing	tree length	tree length	single piece	bunched
3	stump	roadside	log length	log length	bunched	bunched
4	skidtrail	roadside				
5						

SUCCESSOR OPERATIONS: PROCESS, DELIMB, BUCK, TOP, LOAD

REGRESSION EQUATION: Skidding

OPERATION: SKID
MACHINE NAME: RTSchoMed
MACHINE DESCRIPTION NOTES: Rubber Tired Skidder - medium class

ATTACHMENT: cable
HP CLASS: 120 (medium)
SUSPENSION: false
GROUND FIRMNESS (1-5): 3
GROUND ROUGHNESS (1-5): 4
MAXIMUM SLOPE FAVOURABLE (%): -30
TREE DIAMETER MIN (in): 1
MAXIMUM SLOPE ADVERSE (%): 30
MAX (in): 40
UTILIZATION (%): 65
COST ($/PMH): 60
PRODUCTION COST ($/cunit):

	LOCATION		PRODUCT		ACCUMULATION	
	INPUT	OUTPUT	INPUT	OUTPUT	INPUT	OUTPUT
1	stump	landing	whole tree	whole tree	random	bunched
2	skidtrail	landing	tree length	tree length	single piece	bunched
3	stump	roadside	log length	log length	bunched	bunched
4	skidtrail	roadside				
5						

SUCCESSOR OPERATIONS: PROCESS, DELIMB, BUCK, TOP, LOAD

REGRESSION EQUATION: Skidding

OPERATION: SKID
MACHINE NAME: RTSchoLrg
MACHINE DESCRIPTION NOTES: Rubber Tired Skidder - large class

ATTACHMENT: cable
HP CLASS: 170 (large)
SUSPENSION: false
GROUND FIRMNESS (1-5): 3
GROUND ROUGHNESS (1-5): 4
MAXIMUM SLOPE FAVOURABLE (%): -30
TREE DIAMETER MIN (in): 1
MAXIMUM SLOPE ADVERSE (%): 30
MAX (in): 40
UTILIZATION (%): 65
COST ($/PMH): 67
PRODUCTION COST ($/cunit):

	LOCATION		PRODUCT		ACCUMULATION	
	INPUT	OUTPUT	INPUT	OUTPUT	INPUT	OUTPUT
1	stump	landing	whole tree	whole tree	random	bunched
2	skidtrail	landing	tree length	tree length	single piece	bunched
3	stump	roadside	log length	log length	bunched	bunched
4	skidtrail	roadside				
5						

SUCCESSOR OPERATIONS: PROCESS, DELIMB, BUCK, TOP, LOAD

REGRESSION EQUATION: Skidding

OPERATION: SKID
MACHINE NAME: RTSgplSm
MACHINE DESCRIPTION NOTES: Rubber Tire Skidder - small class

ATTACHMENT: grapple | HP CLASS: 90 (small)
SUSPENSION: false
GROUND FIRMNESS (1-5): 3 | GROUND ROUGHNESS (1-5): 4
MAXIMUM SLOPE FAVOURABLE (%): -30 | TREE DIAMETER MIN (in): 1
MAXIMUM SLOPE ADVERSE (%): 30 | MAX (in): 40
UTILIZATION (%): 60
COST ($/PMH): 64 | PRODUCTION COST ($/cunit):

	LOCATION INPUT	LOCATION OUTPUT	PRODUCT INPUT	PRODUCT OUTPUT	ACCUMULATION INPUT	ACCUMULATION OUTPUT
1	skidtrail	landing	whole tree	whole tree	bunched	bunched
2	skidtrail	roadside	tree length	tree length		
3			log length	log length		
4						
5						

SUCCESSOR OPERATIONS: PROCESS, DELIMB, TOP, BUCK, LOAD

REGRESSION EQUATION: Skidding

OPERATION: SKID
MACHINE NAME: RTSgplMed
MACHINE DESCRIPTION NOTES: Rubber Tire Skidder - medium class

ATTACHMENT: grapple | HP CLASS: 120 (medium)
SUSPENSION: false
GROUND FIRMNESS (1-5): 3 | GROUND ROUGHNESS (1-5): 4
MAXIMUM SLOPE FAVOURABLE (%): -30 | TREE DIAMETER MIN (in): 1
MAXIMUM SLOPE ADVERSE (%): 30 | MAX (in): 40
UTILIZATION (%): 60
COST ($/PMH): 70 | PRODUCTION COST ($/cunit):

	LOCATION INPUT	LOCATION OUTPUT	PRODUCT INPUT	PRODUCT OUTPUT	ACCUMULATION INPUT	ACCUMULATION OUTPUT
1	skidtrail	landing	whole tree	whole tree	bunched	bunched
2	skidtrail	roadside	tree length	tree length		
3			log length	log length		
4						
5						

SUCCESSOR OPERATIONS: PROCESS, DELIMB, TOP, BUCK, LOAD

REGRESSION EQUATION: Skidding

OPERATION: SKID
MACHINE NAME: RTSgplLrg
MACHINE DESCRIPTION NOTES: Rubber Tire Skidder - large class

ATTACHMENT: grapple | HP CLASS: 170 (large)
SUSPENSION: false
GROUND FIRMNESS (1-5): 3 | GROUND ROUGHNESS (1-5): 4
MAXIMUM SLOPE FAVOURABLE (%): -30 | TREE DIAMETER MIN (in): 1
MAXIMUM SLOPE ADVERSE (%): 30 | MAX (in): 40
UTILIZATION (%): 60
COST ($/PMH): 79 | PRODUCTION COST ($/cunit):

	LOCATION INPUT	LOCATION OUTPUT	PRODUCT INPUT	PRODUCT OUTPUT	ACCUMULATION INPUT	ACCUMULATION OUTPUT
1	skidtrail	landing	whole tree	whole tree	bunched	bunched
2	skidtrail	roadside	tree length	tree length		
3			log length	log length		
4						
5						

SUCCESSOR OPERATIONS: PROCESS, DELIMB, TOP, BUCK, LOAD

REGRESSION EQUATION: Skidding

OPERATION: SKID
MACHINE NAME: Clam Bunk
MACHINE DESCRIPTION NOTES: Clam Bunk skidder, 15 ton payload, eg. TimberJack 520.

ATTACHMENT: grapple
HP CLASS: 185
SUSPENSION: false
GROUND FIRMNESS (1-5): 3
GROUND ROUGHNESS (1-5): 4
MAXIMUM SLOPE FAVOURABLE (%): -30
TREE DIAMETER MIN (in): 1
MAXIMUM SLOPE ADVERSE (%): 10
MAX (in): 40
UTILIZATION (%): 67
COST ($/PMH): 111
PRODUCTION COST ($/cunit):

	LOCATION		PRODUCT		ACCUMULATION	
	INPUT	OUTPUT	INPUT	OUTPUT	INPUT	OUTPUT
1	skidtrail	landing	whole tree	whole tree	single piece	bunched
2	skidtrail	roadside	tree length	tree length	bunched	bunched
3						
4						
5						

SUCCESSOR OPERATIONS: DELIMB, TOP, PROCESS, BUCK, LOAD

REGRESSION EQUATION: ND

OPERATION: FORWARD
MACHINE NAME: SmallStd
MACHINE DESCRIPTION NOTES: Small Std tire forwarder, payload 10000 lbs.

ATTACHMENT: grapple
HP CLASS: <100
SUSPENSION: true
GROUND FIRMNESS (1-5): 2
GROUND ROUGHNESS (1-5): 3
MAXIMUM SLOPE FAVOURABLE (%): -40
TREE DIAMETER MIN (in): 1
MAXIMUM SLOPE ADVERSE (%): 20
MAX (in): 20
UTILIZATION (%): 64
COST ($/PMH): 74
PRODUCTION COST ($/cunit):

	LOCATION		PRODUCT		ACCUMULATION	
	INPUT	OUTPUT	INPUT	OUTPUT	INPUT	OUTPUT
1	skidtrail	landing	shortwood	shortwood	bunched	bunched
2	skidtrail	roadside			single piece	bunched
3						
4						
5						

SUCCESSOR OPERATIONS: LOAD

REGRESSION EQUATION: ND

OPERATION: FORWARD
MACHINE NAME: SmallWide
MACHINE DESCRIPTION NOTES: Small Wide tire forwarder, payload 10000 lbs.

ATTACHMENT: grapple
HP CLASS: <100
SUSPENSION: true
GROUND FIRMNESS (1-5): 3
GROUND ROUGHNESS (1-5): 3
MAXIMUM SLOPE FAVOURABLE (%): -40
TREE DIAMETER MIN (in): 1
MAXIMUM SLOPE ADVERSE (%): 20
MAX (in): 20
UTILIZATION (%): 64
COST ($/PMH): 74 + track cost
PRODUCTION COST ($/cunit):

	LOCATION		PRODUCT		ACCUMULATION	
	INPUT	OUTPUT	INPUT	OUTPUT	INPUT	OUTPUT
1	skidtrail	landing	shortwood	shortwood	bunched	bunched
2	skidtrail	roadside			single piece	bunched
3						
4						
5						

SUCCESSOR OPERATIONS: LOAD

REGRESSION EQUATION: ND

OPERATION: FORWARD
MACHINE NAME: LargeStd
MACHINE DESCRIPTION NOTES: Large Std tire forwarder, payload 20000 lbs.

ATTACHMENT: grapple
HP CLASS: >100
SUSPENSION: true
GROUND FIRMNESS (1-5): 2
GROUND ROUGHNESS (1-5): 4
MAXIMUM SLOPE FAVOURABLE (%): -40
TREE DIAMETER MIN (in): 1
MAXIMUM SLOPE ADVERSE (%): 20
MAX (in): 20
UTILIZATION (%): 64
COST ($/PMH): 84
PRODUCTION COST ($/cunit):

	LOCATION		PRODUCT		ACCUMULATION	
	INPUT	OUTPUT	INPUT	OUTPUT	INPUT	OUTPUT
1	skidtrail	landing	shortwood	shortwood	single piece	bunched
2	skidtrail	roadside			bunched	bunched
3						
4						
5						

SUCCESSOR OPERATIONS: LOAD

REGRESSION EQUATION: ND

OPERATION: FORWARD
MACHINE NAME: LargeWide
MACHINE DESCRIPTION NOTES: Large Wide tire forwarder, payload 20000 lbs.

ATTACHMENT: grapple
HP CLASS: >100
SUSPENSION: true
GROUND FIRMNESS (1-5): 3
GROUND ROUGHNESS (1-5): 4
MAXIMUM SLOPE FAVOURABLE (%): -40
TREE DIAMETER MIN (in): 1
MAXIMUM SLOPE ADVERSE (%): 20
MAX (in): 20
UTILIZATION (%): 64
COST ($/PMH): 84 + track cost
PRODUCTION COST ($/cunit):

	LOCATION		PRODUCT		ACCUMULATION	
	INPUT	OUTPUT	INPUT	OUTPUT	INPUT	OUTPUT
1	skidtrail	landing	shortwood	shortwood	single piece	bunched
2	skidtrail	roadside			bunched	bunched
3						
4						
5						

SUCCESSOR OPERATIONS: LOAD

REGRESSION EQUATION: ND

APPENDIX III

COMMON SYSTEMS

Whole Tree System

FELL & BUNCH ==>	SKID WHOLE TREES==>	PROCESS AT LANDING
Feller-Buncher * Drive to tree * Swing boom * Cab leveling swing boom * "semi walking"	Grapple skidder Clambunk skidder	Delimber * Stroke boom * Stroke deck Grapple processor Chain flail delimber Loader mounted self aligning delimber

Cut To Length System

FELL & PROCESS TREES AT STUMP==>	FORWARD SHORT LOGS TO LANDING
Feller-Buncher then Processor * Single Grip	Forwarder
Harvester * Single Grip * Double Grip	Forwarder

Tree Length System

FELL & PROCESS TREES AT STUMP==>	SKID TREE LENGTH==>	BUCK TREES AT LANDING
Harvester * Double Grip	Grapple Skidder	Chainsaw Bucking

From Kellogg, L. D., 1991. Mechanized Harvesting Equipment and Systems in the Pacific Northwest. Paper presented at the Mechanized Harvesting Workshop, OSU, December 1991.

Method of Calculation of Rated Footprint Pressure

To make a reasonably fair comparison, footprint area has to be measured in a uniform, standardized manner and at a "standard" sinkage.

A "standard" sinkage of 15% of the overall tire diameter is proposed for the following reasons:

1. It is a "tolerable" normal sinkage for off-road vehicles operating on soft ground. At a sinkage over 15% the motion resistance may start to present problems.
2. It can be proven that R*B is a very good approximation of footprint area at a sinkage of 15% of the overall diameter of the tire. This makes calculation easy.

The same "standard" sinkage is also proposed for tracks.

The "standard" rated footprint pressure for a tire is thus defined as:

$$P=\frac{W}{R*B}\ psi$$

W = wheel load in lbs.

R = tire overall radius (unloaded radius) in inches.

B = tire width (unloaded) in inches.

The standard ground contact pressure for a track is defined as:

$$P=\frac{W}{B(1.25R+L)}\ psi$$

W = track load in lbs.

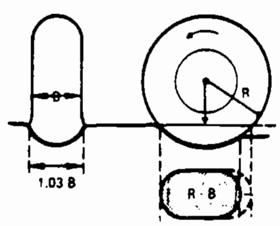
B = track width in inches.

R = track wheel overall radius in inches.

L = the distance between track wheel centers in inches.

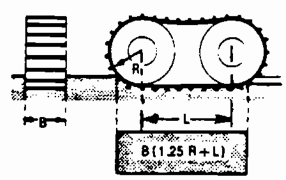
To convert pressure from English to metric units, multiply by 6.895; thus 1 psi = 6.895 kPa

Wheel-Tire



Footprint Area = RxB

Track



Footprint Area = B(1.25 R + L)

Method taken from Appendix I of: Mellgren, P.G. 1980. Terrain Classification for Canadian Forestry. Woodlands Section, Canadian Pulp and Paper Association. 13 p.