MODELING GROUND-BASED TIMBER HARVESTING SYSTEMS USING COMPUTER SIMULATION

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ABSTRACT - Modeling ground-based timber harvesting systems with an object-oriented methodology was investigated. Object-oriented modeling and design promote a better understanding of requirements, cleaner designs, and better maintainability of the harvesting simulation system. The model developed simulates chainsaw felling, drive-to-tree feller-buncher, swing-to-tree single-grip harvester performing felling, and grapple skidder and forwarder in extraction activities. The model can be used to generate stands of trees, simulate felling and extraction processes, and analyze results in terms of cost and productivity. It also takes into account traffic intensity level of extraction machines across the sites and other operational factors. The model was used to evaluate the interaction of stand variables, harvest treatments, machines, and extraction patterns. The results suggest that using two main skid trails to harvest a block minimized traffic intensity. The model can be used to evaluate alternative skidding configurations and their impact on cost, production, and traffic intensity.

INTRODUCTION

Computer simulation has been used successfully in several research projects of forest operations over the last 20 years. The attempts to capture the variability of timber harvesting in mathematical models has fueled a proliferation of diverse models, from regression models to stochastic process models and simulation models (Baumgras *et al.*, 1993). Because simulation was an efficient, low cost method of exploring the intricacies of any system or machine, it could be a valuable asset in identifying weaknesses or oversights of harvesting systems (Hassler *et al.*, 1985).

Side-by-side comparisons could identify the differences of harvesting systems under similar stand and operation conditions (Lanford and Stokes, 1995, 1996). Comparisons, however, cannot be conducted under the very same conditions during field studies. Field studies are also limited by the cost of replicating experiments over a variety of conditions. Field studies capture only a sample of the production rates that occur during the unique conditions observed (Aedo-Ortiz *et al.*, 1997). One way to analyze a wide range of conditions is to build a simulation model that can be run repeatedly with different equipment configurations and working conditions (LeDoux *et al.*, 1994).

An interactive computer simulation program was revised and upgraded recently to evaluate interactions of stands, equipment, and harvest prescriptions typical of current U.S. Forest Service sales (Wang and Greene, 1999). A stand generator was also provided in the system. Chainsaw, move-to-tree feller-buncher, and swing-to-tree harvester in felling and grapple skidder and forwarder in extraction were examined with the program. An intensive simulation experiment was also conducted by using this interactive simulation program to examine the interactions of stand, harvest, and machine factors (Wang *et al.*, 1998). However, interactive simulation is relatively labor-intensive, especially for simulating skidding or forwarding. It seems essential to model timber harvesting numerically and incorporate it with interactive simulation, especially for skidding or forwarding with uniform patterns. Additionally, many of these previous studies modeled either individual harvesting machines or the operations under specified conditions in terms of harvesting costs and productivity. Research on modeling the interactions of stands, machines, and harvest treatments, especially extraction patterns or other environmental impacts of timber harvesting on sites appears to be lacking.

OBJECTIVES

The objectives of this paper are to: (1) model forest stand generation, machine movement, boom movement of swing-to-tree machine, extraction patterns, and traffic intensity of extraction machine across harvested site; (2) define felling algorithms for chainsaw, drive-to-tree feller-buncher, and swing-to-tree single-grip harvester in both partial cuts and clearcuts, and skidding/forwarding algorithms for grapple skidders and forwarders in extraction activities; and (3) conduct an intensive simulation experiment for evaluating the interaction of stands, harvest treatments, machines, and extraction patterns.

EXTRACTION MODELING

Functions modeled for grapple skidder are: move to load, grapple load, travel loaded, and unload. Move to load, load, travel loaded, and unload were modeled for forwarder.

Since two separate modules were adopted, one module performed simulation and the other performed analysis. Elemental time equations for an individual machine are allowed to be modified based on the specific simulation conditions. Changes do not have any effects on the simulations performed earlier in another module.

Extraction Patterns

While interactive simulation allows constant and direct human input to the simulation, it is time consuming and often very repetitive, especially with uniform skidding or forwarding patterns. Therefore, the numerical skidding or forwarding simulation was modeled in the system. Four skidding or forwarding patterns (SP1, SP2, SP3, and FP1) have been modeled so far in the system. They are as follows:

SP1 - free-style skidding (no designated skid trail)
SP2 - skid trail runs through the center of plot (one trail)
SP3 - skid trails going from the landing to the corners of plot (two trails)
FP1 - forwarding along the trails of harvester (forwarding direct to road)

Traffic Intensity

The traffic intensity within each smaller grid (for example 16.5 feet by 16.5 feet) is recorded into a file while performing numerical extraction simulation. Four travel intensity categories for skidder or forwarder were defined in the system as follows (Carruth and Brown, 1996):

TI1 - Trees on the plot have been felled.
TI2 - Trees that stood on the plot have been removed and no other traffic has passed through the plot.
TI3 - Trees that stood on the plot have been removed and trees outside the plot have been skidded through the plot. Passes with a loaded machine are between three and ten.
TI4 - More than ten loaded machine passes have been made through the plot.

After the machine is fully loaded, it will start to return from its current position to the landing in the shortest and easiest way depending on the extraction pattern. The skidding area is divided into 16.5 feet by 16.5 feet cells for recording travel intensity accurately. This 16.5 foot wide grid is used to allow two machines to pass each other on a trail. There are eight possible options for a machine to move from its current position to next position (Figure 1).

An array is used to hold the number of passes a machine traveled loaded through a plot. Suppose the machine is moved from point (X_{i-1}, Y_{i-1}) to point (X_i, Y_i) (Figure 1). In that situation, $X_i > X_{i-1}$ and $Y_i < Y_{i-1}$. A linear equation can be formulated for line segment (X_{i-1}, Y_{i-1}) to (X_i, Y_i). Let,

$$Y = \beta_0 + \beta_1 \times X \qquad \beta_1 = \frac{Y_i - Y_{i-1}}{X_i - X_{i-1}} \qquad \beta_0 = Y_{i-1} - \beta_1 \times X_{i-1} \tag{1}$$

The coordinates of any point on this line can be tracked. It can be determined which grid the skidding machine passed through based on the coordinate as the machine moves from start point to the end point. First, the locations of grids for starting point and ending point need to be calculated, which are represented by a two-dimension array GridL(i, j). Let the grid location of start point (X_{i-1}, Y_{i-1}) be GridL(i, j), the grid location of end point will be GridL(i+m, j-n). Here, m and n are the number of grids that the machine had passed through in both X-coordinate and Y-coordinate directions. Then, the next point is checked starting from (X_{i-1}, Y_{i-1}). The next point could be:

$$\begin{cases} x = (i+1)\times C_w \\ y = \beta_0 + \beta_1(i+1)\times C_w \end{cases} \qquad \begin{cases} y = (j-1)\times C_w \\ x = \dfrac{(j-1)\times C_w - \beta_0}{\beta_1} \end{cases} \tag{2}$$

Here, i = ith cell in X-coordinate;
j = jth cell in Y-coordinate;
C_w = cell width in feet (16.5 feet);

There would be three conditions to record the travel intensity in a grid after we got x-y coordinates for a new point. Another two-dimension array TIP(i, j) was used here to record it.

$$\begin{aligned} &\text{If } y < (j-1)\times C_w, \\ &TIP(i+1, j) = TIP(i+1, j) + 1 \\ &\text{If } x < (i+1)\times C_w, \\ &TIP(i, j-1) = TIP(i, j-1) + 1 \\ &\text{If } x = (i+1)\times C_w \text{ and } y = (j-1)\times C_w, \\ &TIP(i+1, j-1) = TIP(i+1, j-1) + 1 \end{aligned} \tag{3}$$

The above procedure was repeated until the end point (X_i, Y_i) was reached. The number of passes was recorded and accumulated for each grid that the loaded machine passed through as we traced from start point to end point. After the tracking was done along the entire line segment, the number of passes for the loaded machine in each grid is stored in computer memory and saved to a file after the simulation is completed.

SIMULATIONS

Simulation Factors

There are a total of 18 independent combinations of stand, machine, and harvest factors. Each combination was repeated three times for a total of 54 felling experiments. Another 54 extraction simulation runs were performed correspondingly based on the felling results. Each skidding or forwarding operation was examined with three skidding patterns or one forwarding pattern respectively and a total of 126 skidding and forwarding simulation experiments were conducted. The order in which extraction combinations were simulated was randomly assigned. Felling was performed on a 0.4-acre (132 feet by 132 feet) square plot while skidding and forwarding simulations were performed on a 19.6-acre area that was created by replicating the felling plot 49 times (7 by 7 grids). Extraction machine travel was monitored in a smaller grid (16.5 ft. by 16.5 ft.) that is wide enough to allow wide tired machine to pass or two skidders with narrow tires to pass each other. The landing was located at the same point that was in the middle of lower side of the extraction area for each simulation run. Stand, harvest, machine, extraction pattern, bunch size, cycle time, volume per turn, volume per PMH, and traffic intensity of each grid were recorded for analysis once a simulation was done.

Analysis

An analysis of variance (ANOVA) model was used to determine if any differences existed in cycle time, average extraction distance, cycle volume per PMH, and travel intensity categories by stand, harvest, machine, and extraction pattern. The ANOVA model can be stated as follows:

$$Y_{ijkl} = \mu + S_i + H_j + M_k + SP_l + \varepsilon_{ijkl} \qquad i=1,2 \quad j=1,2,3 \quad k=1,2,3 \quad l=1,2,3,4 \tag{4}$$

Where Y_{ijkl} represents the cycle volume, average extraction distance, cycle time, volume/PMH, travel intensity category 1 to 4 respectively, μ is the grand mean of each response variable, S_i is the effect of stand factors, H_j is the effect of harvest factors, M_k is the effect of machine factors, SP_l is the effect of extraction patterns, and ε_{ijkl} is an error component that represents all uncontrolled variability.

Means of cycle time, average extraction distance, cycle volume per PMH, and travel intensity categories were also used to examine the differences of these operational variables by harvest, machine, and extraction pattern.

Results

Cycle volume differed among stands (F = 58.81; df = 1,118; P = 0.0001) and harvests (F = 11.68; df = 2,118; P = 0.0001) but was not significant different between chainsaw and feller-buncher felling (F = 0.01; df = 2,118; P = 0.99159) and among skidding patterns (F = 0.00; df = 2,118; P = 0.9998).

Average extraction distance (ASD) was not significantly different between chainsaw and feller-buncher (F = 0.13; df = 1,118; P = 0.7236) and between stands (F = 0.16; df = 1,118; P = 0.6865). Average skidding distance was significantly different among harvest methods (F = 450.49; df = 2,118; P = 0.0001) and skidding patterns (F = 315.93; df = 2,118; P = 0.0001).

Cycle time was significantly different between stands (F = 107.74; df = 1,118; P = 0.001), among machines (F = 13.44; df = 1,118; P = 0.0004), and among harvests (F = 20.56; df = 2,118; P = 0.0001). It did not differ among skidding patterns (F = 3.435; df = 2,118; P = 0.4106).

The stand (F=1622.9; df = 1,118; P = 0.0001), harvest (F = 157.90; df = 2,118; P = 0.0001), machine (F = 198.54; df = 1,118; P = 0.0001), and extraction pattern (F = 13.84; df = 2,118; P = 0.0001) all affected cords per PMH of extraction significantly. However, hourly skidding production with SP2 and SP3 did not present a big difference.

The proportion of travel intensity category was defined as the number of a grid of 16.5 ft. by 16.5 ft (1/16-acre) in this category over the total number of grids in logging area of 19.6 acres. It was used to evaluate how machine, harvest, and extraction pattern affected the travel intensity across the harvested site. Travel intensity category 4 was not significantly different among felling machines (F = 0.01; df = 1,118; P = 0.9237) but it differed significantly between stands (F = 80.48; df = 1,118; P = 0.001), among harvests (F = 14.33; df = 2,118; P = 0.001), and among skidding patterns (F = 76.63; df = 2,118; P = 0.001). Travel intensity category 1, 2, and 3 were also significantly different among stand, harvest, and skidding pattern.

Mean extraction distance increased sharply when moving to the partial cuts from clearcuts (Table 1). The shortest mean extraction distance of 527 feet was presented with skidding pattern 1 in clear cuts and increased to 867 feet with skidding pattern 2 in single-tree selection cuts. The mean extraction distances with skidding pattern 3 and forwarding pattern 1 were similar. Hourly production was consistently highest in clearcuts and lower in partial cuts. Shelterwood harvests resulted in lower hourly production than single-tree selection cuts due to the smaller size of trees removed. Hourly extraction production also varied with skidding or forwarding patterns. Forwarding presented higher hourly production than skidding. Skidding with pattern 1 always resulted in higher hourly production than with patterns 2 and 3.

Travel intensity category 4 (TI4) was the level of most concern since it causes the most damage to the soil (Table 2). About 25% and 7% of the logging area was in TI4 with SP1, SP2 and SP3 after skidding, and only 3% of the same area in TI4 after forwarding. The areas of TI4 after forwarding were smaller than that after skidding. Skidding with SP1 always resulted in a higher proportion of TI4 than with SP2 and SP3 that used the designated skid trails. The proportions of TI4 with SP2 and SP3 were also similar. Harvest methods also affected the travel intensity. Since clearcut produced more bunches with higher cords per acre, the proportion of TI4 in the clearcutting area was higher than ones in shelterwood and single-tree selection cutting areas. Since most soil compaction occurs during the first three to six passes (Froelich et al., 1981), TI3 and TI4 can be added together to illustrate the total area that was impacted with three or more passes by a loaded machine. TI3 and TI4 varied from 60% for SP1 to 49% for SP2 to 38% for SP3 in clearcuts with chainsaw and grapple skidder system and results were very similar for the feller-buncher and grapple skidder system. Harvester and forwarder resulted in the TI3 and TI4 of 19% in clearcuts. TI3 and TI4 also varied with harvest methods and decreased from clearcuts to shelterwood to single-tree selection method.

The three harvesting systems were also examined based on their production per week and cost per unit on-board truck. A hydraulic loader was used to load trucks in the skidder systems. Other handling costs were assumed to be equal for the three systems. Their production rates were determined by the machine productivity in the system. Two chainsaws and one skidder were used in the chainsaw/skidder system, one feller-buncher and two skidders in feller-buncher/skidder system, and one harvester and one forwarder in harvester/forwarder system. These data showed that felling was the limiting function in harvester/forwarder systems. Skidding, however, was the limiting function in feller-buncher/skidder and chainsaw/skidder system. System production decreased from clearcuts to single-tree to shelterwood and also varied decreasingly from SP1 to SP3 to SP2. The feller-buncher and grapple skidder system was the most productive system ranging from 254 to 350 cords/week with the harvester and forwarder system ranking second with production ranging from 187 to 244 cords/week. The chainsaw and grapple skidder system was the least productive with weekly production of between 106 and 144 cords (Table 3).

System costs per unit were calculated on-board truck prior to hauling using assumptions of machine rates (Miyata, 1980). Labor was paid $10.00 per hour plus additional labor related costs equal to 40 percent of wages. Salvage value of the machine was 20 percent of its purchase price. Interest, insurance, and tax were assumed as 15 percent. Fuel and lubricants were $1.75/gal and $4.65/gal respectively. The total cost of a representative chainsaw was $17.55 per PMH (Kluender, *et al.*, 1998). Mechanical availability of the chainsaw was assumed at 50 percent. Building cost of skid trails was assumed $6.0 per 100 feet (Erickson and Hassler, 1991). Other assumptions varied by machine.

Comparing the three systems, the feller-buncher/grapple skidder system in clearcuts and SP1 with the cost of $21.82 per cord was least expensive. The harvester/forwarder system was the second (Table 3). The chainsaw/grapple skidder system in shelterwood and SP2 was the most expensive at $37.05 per cord. System costs also varied increasingly from clearcuts to single-tree selection to shelterwood method and from SP1 to SP3 to SP2. In the feller-buncher/skidder system, for example, the cost in shelterwood and SP2 was $29.81 per cord or 26.7 percent more. The cost in single-tree selection and SP2, however, was $25.39 per cord or 8.0 percent more compared to clearcuts of $23.49 per cord in SP2. Similarly, in the feller-buncher/skidder system, the system cost in single-tree selection was $25.43 per cord in SP2 or 8.6 percent more, and was $25.40 per cord in SP3 or 8.5 percent more than $23.42 per cord in SP1. The difference costs between system in SP2 and in SP3 were offset by the building costs of skid trails. If the average size of trees to be harvested was bigger, for example, in single-tree selection cuts, the cost of the harvester/forwarder system at $26.31 per cord would be competitive to the feller-buncher/grapple skidder system in SP2 with a cost difference of $0.88 per cord or 3.5 percent more.

DISCUSSION

Object-oriented modeling techniques (OMT) are a viable method for modeling timber harvesting systems and examining the effects of stand, harvest, machine, and extraction pattern factors on harvesting operations and forest sites. The timber harvesting simulator developed with OMT is a Window standard system and no programming skills or specific computer knowledge are required to perform it. The graphical user interface (GUI) also provides the user an easy access to any part of the system.

Numerical simulation with predefined extraction patterns efficiently reduced simulation time and permitted exploration of more alternatives. Currently, the numerical extraction simulation took a few seconds while it used to take 50 to 190 minutes with interactive simulation (Wang and Greene, 1999). Machine travel was monitored in each felling plot of 132 ft. by 132 ft. with interactive simulation. This is clearly too coarse a measure. After a smaller grid of 16.5 ft. by 16.5 ft. was adopted in numerical simulation, the travel intensities were much more accurate than using a 132 ft. by 132 ft. grid since they were recorded in 3136 small cells on the same area of 49 0.4-acre felling plots. It was proved that the accuracy of travel intensity recording was improved greatly using this smaller grid. Only about 25%, 5%, 6%, and 2% of logging area reached TI4 after skidding with SP1, SP2, and SP3 and after forwarding with FP1 in comparison with about 50% and 30% of TI4 after skidding and forwarding in the same area using the 132 ft. by 132 ft. grid (Wang *et al.*, 1998).

The simulation study also found that travel intensity, mean extraction distance, and hourly extraction production were significantly affected by extraction patterns while cycle time and volume were sensitive to stand and harvest method. Skidding with SP1 gave the shorter extraction distance, lower cycle time, and higher hourly production than with SP2 and SP3 because SP1 was defined as a free-style skidding and no designated trails were used. The hourly skidding production with SP3 was a little bit higher than that with SP2. Since the designated skid trails were used in SP2 and SP3, skidding with SP1 presented a high level of TI4 in comparison with the level of TI4 with SP2 and SP3 after skidding. The forwarder always presented lower proportion of TI4 and higher hourly production than the skidder since the forwarder's higher holding capacity resulted in fewer passes to extract logs. The average extraction distances with SP3 and FP1 were about the same due to their similarity.

Generally speaking, the feller-buncher/skidder system was the most productive compared to the harvester/forwarder and chainsaw/skidder systems. System production varied decreasingly from SP1 to SP3 to SP2. Similarly, system cost varied increasingly from SP1 to SP3 to SP2, but system costs in SP2 and SP3 were very close. Extraction with SP3 always resulted in lower TI3 and TI4 compared with skidding with SP1 and SP2. Skidding with the designated skid trails is recommended to use in order to reduce the high-level travel intensity on logging sites. Results suggest that higher traffic intensity TI3 and TI4 could be reduced by about 22% using SP3 instead of SP1, but about $1.6 per cord or 6.0% more is needed to be paid for such tradeoffs.

However, the terrain conditions of forest site were not considered in the model. The system also does not simulate the residual stand damages in partial cuts. The system should be modified to allow use of irregular polygons whose boundary data can be obtained using GPS unit or from digitized maps or photos. In the future, it could be used as a harvest planning tool to layout a planned timber sale and examine production, cost, and other factors. Further simulation will be conducted to vary the landing locations and payload size of the extraction machines.

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Table 1. Operating variables affected by machine, harvest, and extraction patterns in extraction.[a]

Harvest	Chainsaw Grapple skidder SP1	Chainsaw Grapple skidder SP2	Chainsaw Grapple skidder SP3	Feller-buncher Grapple skidder SP1	Feller-buncher Grapple skidder SP2	Feller-buncher Grapple skidder SP3	Harvester Forwarder FP1
	Volume per turn, cords						
Clearcuts		0.79			0.80		3.98
Shelterwood		0.75			0.73		3.79
Single-tree		0.81			0.83		3.88
	Average extraction distance, feet						
Clearcuts	527	672	655	529	666	651	655
Shelterwood	586	736	714	599	734	713	716
Single-tree	696	853	833	685	867	842	830
	Cycle time, minute						
Clearcuts	8.2	8.8	8.7	6.8	7.3	7.2	32.1
Shelterwood	10.6	11.1	11.1	8.5	8.9	9.0	37.8
Single-tree	7.9	8.5	8.4	7.3	7.9	8.1	33.7
	Volume per PMH, cords						
Clearcuts	6.0	5.6	5.7	7.3	6.7	6.8	10.5
Shelterwood	4.7	4.4	4.5	5.7	5.3	5.4	8.88
Single-tree	5.8	5.4	5.5	6.8	6.2	6.3	10.1

[a] Six simulations per cell.

Table 2. Proportion of felling grids in each travel intensity category by machine, harvest, and extraction patterns after felling and extraction.[a]

Harvest	Travel intensity	Chainsaw Grapple skidder SP1	Chainsaw Grapple skidder SP2	Chainsaw Grapple skidder SP3	Feller-buncher Grapple skidder SP1	Feller-buncher Grapple skidder SP2	Feller-buncher Grapple skidder SP3	Harvester Forwarder FP1
		(%)						
Clearcuts	TI1	15	21	25	14	16	22	66
	TI2	24	30	37	24	33	42	15
	TI3	36	42	31	37	46	30	16
	TI4	24	7	7	25	5	6	3
Shelterwood	TI1	22	35	36	23	35	41	69
	TI2	32	36	38	30	31	34	18
	TI3	32	26	20	32	30	19	11
	TI4	14	3	6	15	4	6	2
Single-tree selection	TI1	25	46	49	24	37	41	70
	TI2	30	24	29	32	34	37	18
	TI3	33	28	17	32	26	17	11
	TI4	12	2	5	12	3	5	1

[a] Six simulations per cell and using the system described by Carruth and Brown in 1996.

Table 3. System productivity and on-board truck cost comparisons.

	Harvesting System and Extraction Pattern						
	Chainsaw and Grapple skidder			Feller-buncher and Grapple skidder			Harvester and Forwarder
	SP1	SP2	SP3	SP1	SP2	SP3	FP1
	(Cords/week)						
Clearcuts	144	134	137	350	322	326	244
Shelterwood	113	106	108	274	254	259	187
Single-tree	139	129	132	326	298	302	235
	($/cord)						
Clearcuts	27.71	29.04	28.92	21.82	23.49	23.41	25.35
Shelterwood	35.37	37.05	36.88	27.94	29.81	29.72	33.00
Single-tree	28.66	30.14	30.12	23.42	25.43	25.40	26.31

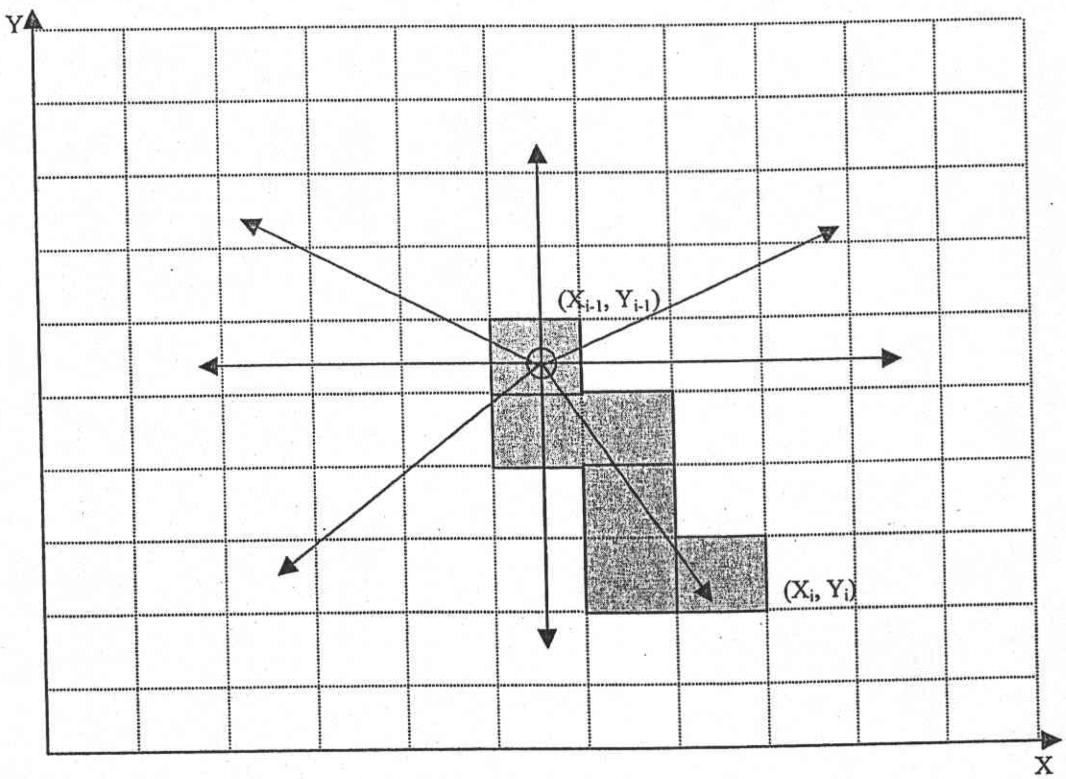

Figure 1. Skidder or forwarder's movement.


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