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ANALYSIS OF FIREWOOD PRODUCTION BY DISCRETE EVENT SIMULATION

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Abstract: *modeling approaches can be divided into three groups: econometric, analytic and simulation. In the last decade, different studies in forest operations confirm that modeling approaches and techniques have been applied with regard to the time horizon of the planning and analysis. At tactical and operational level simulation seems to offer the greatest applicability of modeling. Discrete-event simulation (D-es) allows the use of non linear and linear production functions. Besides the interactions between model elements can be described and the effects of random processes can be modeled.*
In this study a D-es has been developed to analyze firewood production in a mountain area in the North-eastern Italy. The D-es is applied in the modeling of harvesting, extraction (Full Tree System), processing of roundwood into wood assortments (cross-cutting and sorting), off-road and on-road transport.
In order to estimate production functions, field studies were conducted to gather data about the different operations linked in the model. Field survey on primary and secondary forest road network, information on localization of the landings and on the forest road network extension and its distinctiveness parameters were collected.
Extraction volume and extraction paths, forest landings and transshipment site locations were used as variables in the model. In addition the interactions between model elements and parameters were examined by the effects of random processes.

1. Introduction

The simulation is the process of building a model of a real or proposed system to study the performance of the system under specific conditions. A simulation model could be classified as being static or dynamic, deterministic or stochastic and discrete or continuous (Bank et al. 2005).

In the last decade several studies concerning forest operations have seen the application of dynamic, stochastic and discrete simulation. Dynamic because they analyzed the effects of changing variables and the workflow of the system according to the simulation time, stochastic because they considered randomness of observation and discrete because the state variable changes only at a discrete set of point in time. This type of simulations are generally called discrete event simulations (D-es). They are developed generally to analyze the behavior of a system defined as a collection of entities, usually workers and machine, that act and interact toward the accomplishment of some logical end over time (Law and Kelton, 1991).

Asikainen (1995) and Ziesak et al. (2004) reported some advantages of the D-es simulation techniques. One of these advantages is the capacity of this application to analyze discrete and complex real-world situations that cannot be solved by analytical operational methods because of various interactions between the system components. Besides the approach of D-es lets to describe the interactions between the system elements and to model the effects of random processes.

At tactical level, many D-es models were developed for the analysis of the efficiency in the transport interactions. Asikainen (2000) modeled chipping terminal logistic by a D-es model which was based on a manufacturing simulator in order to compare different loading and transport technologies. In this study chipping into truck, chipping onto ground and loading using a wheeled loader, long-distance transport by truck with draw-bar trailer, by truck with a semitrailer and by a truck with interchangeable platforms were considered.

The cost-effective patterns of hardwarders for forest machine contractors in different logging structures and conditions were investigated by Väätäinen et al. (2006).

A D-es model was also programmed to find optimal set-ups for the supply chain of crushed material made from stumps at different road transport distances. The simulation model was based on the continuous supply of crushed material from landings to a district heating plant (Asikainen, 2010).

Recently, a D-es model was developed to find the optimal setups for the timber yarding-processing-truck transport system in mountainous condition using a logging site and transport distance database as input (Asikainen et al. 2010).

Applications of D-es model concerned also the analysis of interaction at operational level for studying the cost-efficiency of single machine or specific operation systems. By changing simulation inputs and observing the results outputs, machine and system behaviors can be studied and compared with different simulation runs. This allows to largely deterministic base simulations that can be carried out to illustrate the effects of machine interactions.

Wang and LeDoux (2003) modeled ground-based timber harvesting system by a object-oriented model from felling to extraction in order to evaluate the interaction of stands, harvester treatments, machines and extraction patterns.

McDonagh et al. (2004) constructed a model that can simulate harvesting system production efficiency with changing stand and terrain parameters. Four common southeastern US harvesting systems were included in the model. The model includes functions, adjustable by the user, that quantify the efficiency of each harvest system is measured with respect to terrain parameters (slope and average extraction distance).

Talbot and Suadicani (2005) compare two chipping operation systems in thinning by evaluating bin size, chipper productivity, in-field extraction distance and forest-road haulage distance.

Yoshimura and Hartshough (2007) evaluated new concepts of cable harvesting systems for estimating the effect of innovative techniques on biomass harvesting in steep terrain.

Multi-stem mechanized harvesting operation was analyzed in South Africa condition by comparing the current real system to two hypothetical systems. The alternative systems were based one on modifying the operation procedures but by considering the same machines and equipments of the current system, the second by chancing also the machine and the equipments (Hogg et al. 2010).

1.1. Aims

In this study, the development and the application of a D-es model aims to evaluate the influence of the extension of the secondary forest road network on the energy-wood supply by considering the interaction between three main transportation system (extraction, off-road and on-road transportation). The D-es model will be defined on the analysis of an existing supply chain of energy-wood and its workflow. The alternative systems will consider the change of the transportation in terms of extension of the forest road network and two operational level of the landings.

2. Materials and methods

The model is composed in four main blocks: extraction process, cross-cut operation at landing, off-road transport and on road transport. The D-es model is built with Witness simulation package (Lanner, 2007).

2.1. Study area

Study area was placed in the Belluno province, in Northeastern part of Italy, latitude N 46.1237 – 46.1167, longitude E 12.4503 – 12.4661. The forest stand is largely composed of beech trees (*Fagus sylvatica*) unless sporadic individual of Norway spruce tree (*Picea abies*). The average growing stock is 423 m^3 ha^{-1} with a mean high of 22 m and a mean rate of growth equal to 7.6 m^3 ha^{-1}. The altitude ranges from 1 248 m to 1 398 m a.s.l. The adopted silvicultural system is the shelterwood method and the analyzed operation regards a shelterwood selection cut with a felled mass of 776 m^3 on an area of about 14 ha (exploitation percent equal to 15 %). The mean diameter of the felled trees was 24 cm.

2.2. The workflow of the energy-wood supply chain for firewood production

The investigated forest operation concerned the extraction of energy-wood for firewood production by the method of the Full Tree System (FTS), the processing of full tree into logs (4-6 m length) and into small assortments of 1.1 m length and three different classes of diameter (< 10 cm, 10-15 cm, 15-20 cm), the off-road and the on-road transport.

The extraction operation was ground based and involved one tractor and winch. This operation was performed by two operators, one driving the tractor and one preparing and hooking the loads (generally full trees). At the landing 4 operators were working. One was involved in the piling operation of logs using a crane (60 kN m) attached to a tractor (74 kW) and located at the landing and in front of the cross-cutting area. When full trees arrived to the forest landing, the same operator grappled and moved the unhooked load into the cross-cutting area. At the same time the tractor and winch could come back to the loads at stump sites for a new extraction cycle. The same operator on the tractor with the crane pilled logs and bundles in piles (maximum 4-4.5 m height) which were located at the right and left side of the same tractor. Other two operators cross-cut the full trees while the remaining operator was mainly busy to sort, according to their diameters (< 10 cm, 10-15 cm, > 15 cm), the small assortments into three different frames which were used for assembling the bundles (70 cm diameter).
Logs and bundles were thus transported off-roads to the transshipment site on tractor roads by a tractor (81 kW) with a 4WD trailer system and a payload capacity of 11 t. Transport on public road to terminal was performed, generally one or two time per day, by a 4x2 WD truck (294 kW) and trailer system with a total payload of 22 t.

2.3. Elements and parameters of the D-es Model

In order to define the cycle time for extraction, processing full tree in logs and bundles, off-road transportation and on-road transportation a time study was sorted out during May and June of 2009.

Extraction was studied by the stop-watch method. Data collection of the possible factors affecting time consumption of extraction considered: loads volume (generally a single tree or a tree cut in two pieces), driving loaded and driving empty distance, slope gradient of the extraction path. Load volume was determined after the cross-cut process by measuring the average diameter and the length of each single logs and by recording the number of small assortments according the frame where they were sorted. Processing full tree at landing into logs and bundles of small assortments was studied with the support of a digital video-camera and work sampling method. Productivity factors was also the cross-cut volume. The off-road and on-road transportation was also studied by stop-watch method with the aim to determine the average speed for travel loaded and travel empty and for loading and unloading time.

The data collected of the traveled extraction distance, the slope gradient of the trails (travel loaded and travel empty) and the extracted loads were used to evaluate the optimal distribution for the same data on the probability plots and goodness-of-fit tests for the generating a realistic dataset of loads as input for the D-es model. The goodness-of-fit testes were evaluated by SPSS 17 statistical package software (SPSS, 2009) at the confidence interval of 0.05.

Also delay times of the extraction and the cross-cutting operation (excluded waiting time generated by the interaction between the system elements) were analyzed in order to evaluate the distribution of the delay time in terms of interval time between delays and their time.

Table 1. Elements and parameters of the D-es model

Model element	Cycle-time/Breakdown	Function/Distribution	Unit
Extraction	Unloading (unhooking) (PSH_0)	Mean = 46.93 St.Dev = 23.6 (normal dist.)	sec
	Loading (hooking) (PSH_0)	Mean = 327.3 St.Dev = 114.1 (normal dist.)	sec
	Travel loaded (PSH_0)	$e^{(2.3542)} *Load^{(0.15314)}*Load^{(0.64003)}$	min
	Travel empty (PSH_0)	$e^{(1.3219)} * Slope^{(0.13602)}*Distance^{(0.74024)}$	min
	Delays time	Mean = 6.115 St.Dev = 4.769 (lognormal dist.)	min
	Interval delay time	Mean = 27.58 St.Dev = 7.38 (normal dist.)	min
Cross-cutting	Cross-cutting (PSH_0)	$e^{(0.3348)} * e^{(1.6343*Load)} * Load^{(-0.5017)}$	min
	Delay	Mean = 2.111 St.Dev = 1.278 (normal dist.)	min
	Interval delay time	Mean = 27.58 St.Dev = 7.38 (lognormal dist.)	min
Off-road transport	Loading	Mean = 8.86 St.Dev = 0.765 (normal dist.)	min
	Travel loaded	Mean = 6.37 St.Dev = 0.269 (normal dist.)	km h^{-1}
	Unloading	Mean = 9.48 St.Dev = 1.004 (normal dist.)	min
	Travel empty	Mean = 7.10 St.Dev = 0.368 (normal dist)	km h^{-1}
On-road transport	Loading	Mean = 15.93 St.Dev = 0.975 (normal dist.)	min
	Travel loaded	Mean = 34.6 St.Dev = 2.115 (normal dist.)	km h^{-1}
	Unloading	Mean = 18.71 St.Dev = 1.176 (normal dist.)	min
	Travel empty	Mean = 35.7 St.Dev = 2.016 (normal dist.)	km h^{-1}
Slope gradient	Travel loaded	Mean = 13.748 St.Dev = 4.435 (lognormal dist.)	%
	Travel empty	Mean = 12.286 St.Dev = 4.473 (lognormal dist.)	%
Extracted loads	-	Mean = 1.046 St.Dev = 0.503 (lognormal dist.)	m^3

PSH_0 = Productive system time without delays

2.4. Validation and experiment design

The D-es model was built according to the investigated situation. During the model construction the logical proceeding of work sequences where tested by running the model step by step and observing the interaction between all the element by graphic and value outputs (Figure 1). The validation considered a run of 15 repetitions by considering a warm-up period of 480 min, using several different sets of random number streams and running for 10 000 min. The simulated output of the supplied wood (1.5-1.8 truck and trailer per one working day - 480 min) corresponded to the average registered from the forest enterprise (from 7 to 9 truck and trailer every 5 working days).

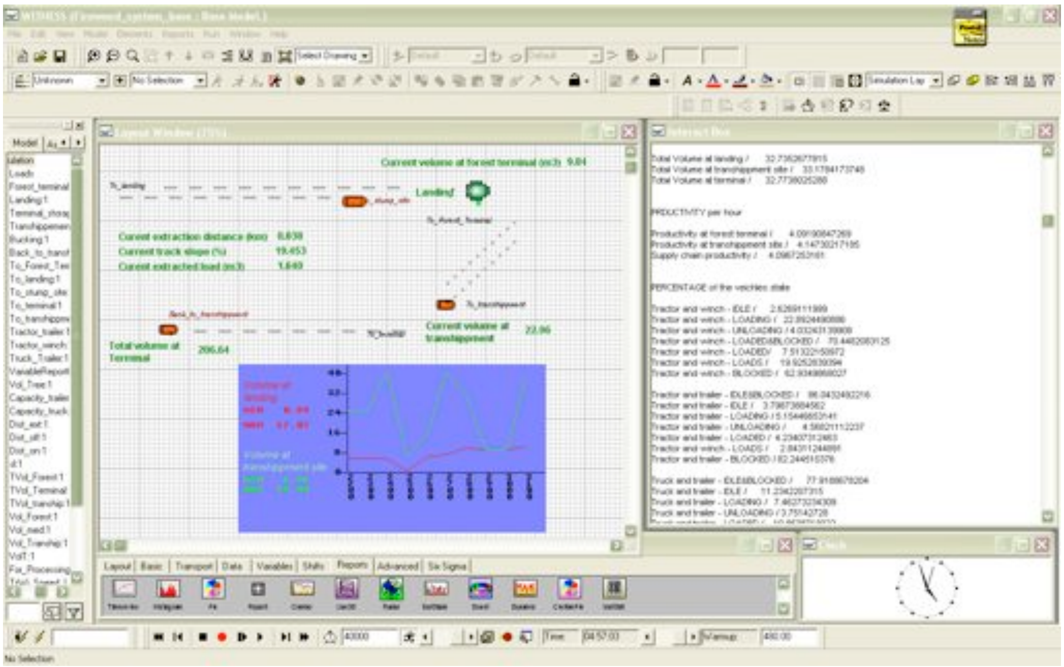

Figure 1. Layout of the D-es model of energy-wood supply chain for firewood production

2.5. Experimental design

The first experiment design considered 7 different extension (situation B corresponds to the current situation) of the transportation network according to 7 different locations of landings (Table 2; Table 3).

Table 2. Experiment design

Exp	Landing							
A	A	-	-	-	-	-	-	-
B	**A**	**B**	-	-	-	-	-	-
C	A	B	C	-	-	-	-	-
D	A	B	C	D	-	-	-	-
E	A	B	C	D	E	-	-	-
F	A	B	C	D	E	F	-	-
G	A	B	C	D	E	F	G	-
H	A	B	C	D	E	F	G	H

Table 3. Main description of the distance parameters for extraction, off-road and on-road transportation according to the increment of the number of forest landing (by GIS analysis)

	Site	EXTRACTION			Site	Road Network	OFF-ROAD		ON-ROAD	
		distance				density	distance		distance	
EXP	Landing	Mean	StDev	Sum	Transhippment	Density	Mean	Sum	Mean	Sum
-	n°	m	m	km	n°	m ha^{-1}	m	km	km	km
A	1	230	146	336	1	7.73	750	137	31.20	1981
B	**2**	**116**	**60**	**169**	**2**	**14.48**	**968**	**177**	**31.85**	**2022**
C	3	79	36	116	2	26.14	1112	203	32.11	2038
D	4	68	30	99	2	38.44	1254	229	31.92	2026
E	5	65	30	95	2	38.44	1277	233	31.59	2005
F	6	61	30	89	2	56.92	1314	240	31.55	2003
G	7	58	29	84	2	68.16	1263	230	31.73	2014
H	8	53	26	77	2	68.16	1238	226	31.66	2009

Two different condition of unhooking loads at landing were also considered. In the investigated situation, the area of the two landings were not enough wide for more than one load (full tree) in front of the cross-cutting area (*ex-ante* condition). For this reason when extraction distance were not so long, the tractor and winch was waiting for the unhooking until the cross-cutting area was free from the previous load. It was so supposed a scenario with wider landings in order to let the tractor and winch to unload the loads even if the previous load will be still in the cross-cutting area (*ex-post* condition).

For each simulation scenarios, the spatial distribution of the loads was the same. The distribution of the load corresponds to the location of the stump site. These were determined by generating a input dataset of 731 loads. For each loads the following variables were determined according to the distribution probability curves previously defined: extraction distance for each scenarios according to the average value and the StDev reported on Table 2 (lognormal distribution), trail slope gradient for travel loaded and travel empty (normal distribution) and volume (lognormal distribution). Loads were then randomly distributed within the cutting area (surveyed by GPS – Garmin 60 CSx) by using the *Generating random points tool* of ArcGIS 9.3–ArcInfo which randomly places a specified number of points within an identified area (ESRI, 2009).

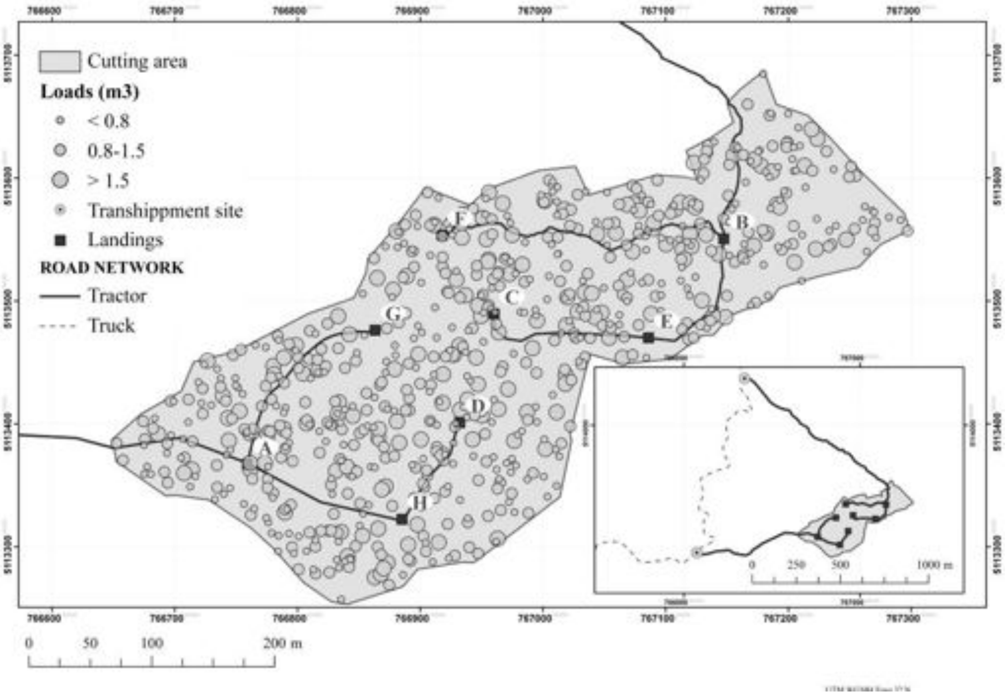

Figure 2. Layout of the studied area with the distribution of the loads and the maximum supposed road network extension and its landing location

3. Results

According to the defined experimental design, some of the main results are reported. The working time distribution of the *ex-ante* condition for the unloading work cycle of extraction operation increases with the increment of the number of landings and the reduction of the extraction distance (Figure 3).

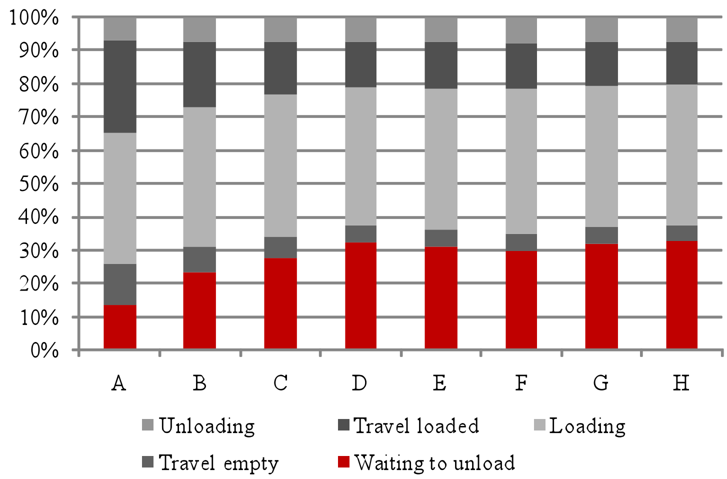

Figure 3. Working time distribution for extraction system according to the increment of the landing number in the *ex-ante* condition

The increment of the productivity of the cross-cutting operation grows slightly (Figure 4). The maximum productivity is reported in the condition G with 7 landings and a density of the secondary forest road of 68 m ha^{-1}.

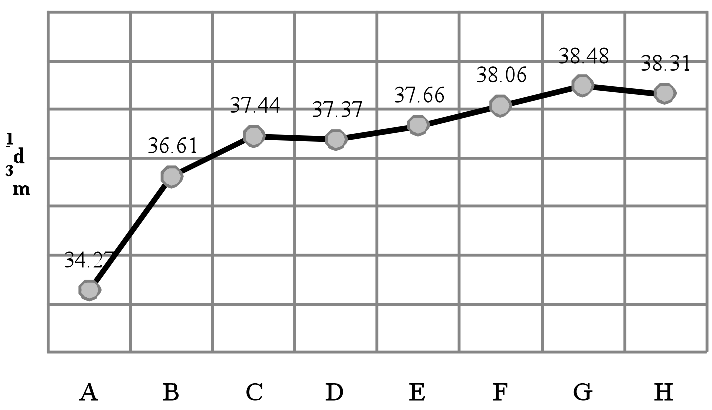

Figure 4. Output of cross-cutting operation according to the different scenarios

The productivities of cross cutting operation for the current situation with two landings (Scenario B) and with the hypothetical situation of 7 landings (Scenario G) are reported in Figure 4. The same Figure 4 compares the productivities of the conditions *ex-ante* and the condition *ex-post*.

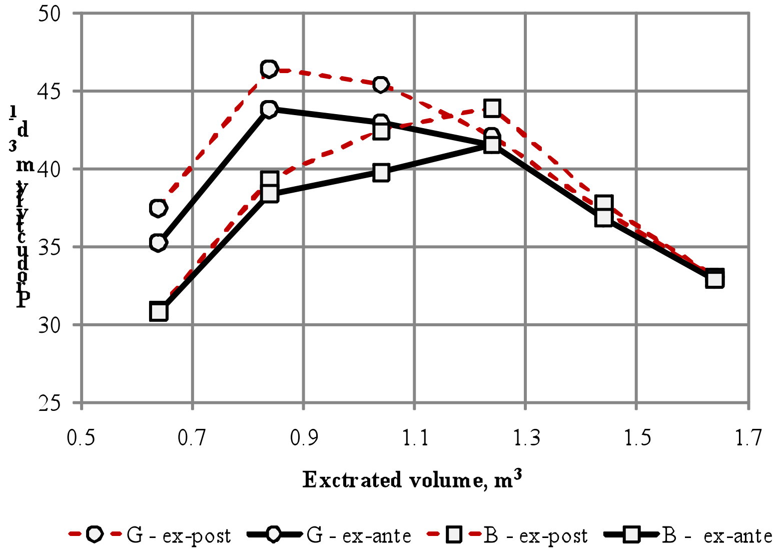

Figure 4. Output for scenario B and scenario G

4. Discussion and conclusions

This paper concerned a first development and application of D-es model for analyzing the energy-wood supply chain for firewood production.

The study has presented an overview of a simulation approach to evaluate the influence of the extension of the forest road network on the energy-wood supply by considering the interaction between three main transportation system (extraction, off-road and on-road transportation).

Focusing on the interaction between extraction and cross-cutting operation, the increment of the extension of the forest road network slightly influences the productivity at landing. A different result can be obtained if the landing area is improved in terms of buffer capacity and operational efficiency. The possibility to unhooking the loads without wait for the end of the cross-cutting operation affects the productivity differently in respect of the average volume of the load (Figure 4).

This first approach for the D-es model for energy wood supply chain for firewood production still requires improvement in terms of scenario definition and output. The next steps will include cost and environmental impacts output in order to forecast also economic and ecology result.

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