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Optimal Forest Road Density Based on Skidding and Road Construction Costs in Iranian Caspian Forests

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ABSTRACT
Information on the productivity, costs and applications of the logging system is a key component in the evaluation of management plans for the rehabilitation and utilization of Caspian forests. Skidding and road construction costs are expensive forest operations. Determining the optimum forest road network density is one of the most important factors in sustainable forest management. Logging method is an important factor to determine the optimum road network density. In this research, in order to determine the optimum road network density, skidding cost and road construction cost were calculated. Linear programming model was used in order to reduce the skidding costs and to determine the optimal forest road network density. Our aim was to determine the minimum skidding cost for Timber Jack and Clark skidders for different average skidding distance. The results showed that it is less costly if Clark skidder is used for skidding. Then the optimal road network density at this manner was 8 m/ha.

Keywords: Forest road network, Optimization modeling, Linear programming, Caspian Forests

INTRODUCTION
In Caspian forests, most timber is extracted by different methods of ground skidding and the logging methods used is cut to length and tree length. Forest roads are generally planned and constructed by considering physical, economical, and environmental requirements (Akay, 2006). Temperate forest in the north of Iran has been extracted by using of wheeled skidders in the early 1970's and nowadays are still the most widely used methods. Wheeled skidders requiring of optimum road spacing is the main problem, because of their costs. In fact, the spacing of forest roads can have a profound effect on the cost of harvesting and transportation wood. If roads are spaced too closely, the cost of building the roads will be prohibitive. If roads are spaced too far apart, the time required to skid wood to road side or to a landing will be prohibitive. Optimal road spacing can also be influenced by other factors having impact on optimal road network such as logging method, landing costs, overhead costs, equipment opportunity costs, price of product, taxation policies, road with and size of landing, skidding pattern, profit of logging contractor, slope and topography and soil disturbance, forest potential for road construction, accessing timber harvest site (Segebaden, 1964; Bryer, 1983; Sessions, 1986; Liu and Corcoran, 1993; Yeap and Sessions, 1993; Heinimann, 1997; Najafi et al, 2008).

There are many different methods related to determining of road construction, road costing, road spicing, skidding costs and generally optimal road network at different logging methods and different forests (Tan 1999; Chung and Sessions, 2001; Heralt L. 2002; Demir and Tolga, 2004; Anderson and Nelson, 2004; Aruga, K. 2005; Coulter et al, 2006; Ghffarian and Sobhani, 2007; Najafi et al, 2008). Forest harvesting costs account for more than the half of forest management cost and in Iran; it sometimes reaches up to 65 percent (Sarikhani, 1990). Therefore, it is very important to optimize the related harvesting costs in any forest management activities and at the same time by increasing the length of road technically, decrease road distance and let the cost of wood transportation comes down. At present, forests administrators are concerned with these issues and try to find suitable approaches to reduce the costs and increase the efficiency. On the other hand, not only cost of road and wood transportation and extraction must come down, but also environmental affect have to come down too. In fact, the cost of wood transportation and road constructing should be balanced by a technical forest road network that accesses the forest surface with the minimized road length (Eghtesadi et al, 2002).

In most studies carried out on the evaluation of systems efficiency and operation of harvesting machinery the time study techniques and statistical models were used for estimating the time and cost of operation (Pir Bavaghar et al, 2007; Eghtesadi, (2008). Favreau and Gingras (1998) studied the amount of production and cost of it at different stages of production (felling, bucking, loading and extraction) on full tree logging and cut to length logging methods. They concluded that the wood production cost per cubic meter in cut to length logging method at extraction stage was higher than full tree logging method. They found that length of logs, skidding distance, topographical conditions and operators skills were important effective variables on production cost. The development of mathematical equations of the skidding time is an effective method for estimating the production cost. Therefore the independent variables entered into the models must be flexible and represent the real life situation of the systems (Goulet et al., 1979). Ledoux and Huyler (2001) compared large cut to length and small cut to length system of harvesting in terms of production and operating costs with different machine utilization rates in broad leave forests of eastern USA. In their research they used time study method and examined the effective factors in extracting logs from feeling gaps to landings on the side of road. They concluded that the most important effective factors were load volume in each turn, skidding distance and number of logs in each turn. Picman and Pentek (1998) calculated optimal road density of 14.7 m/h for ground based skidding system in Croatia. The results of researches carried out on the efficiency of ground skidding systems in northern forest of Iran showed that skidding distance has direct and linear relation with skidding costs and in other studies they showed that optimal road density ranged from 6 to 28 m/ha for different areas (Mostafanejad, 1995; Naghdi, 2004; Naghdi and et al. 2005 and Eghtesadi, 1991, Ghaffarian and Sobhani, 2008). Optimum road density is an important factor that helps forest engineers to optimize the harvesting costs with using a suitable forest road network (Ghaffarian et al. 2003). There is a direct counter relation between skidding distance and road spacing (Tan,1992).

MATERIALS AND METHODS

Study Area

This study was carried out in compartment 27 of 10th district in Shafarood forest, with the altitude ranging between 20 and 650 meters and average annual precipitation of 1000 mm. The forest was uneven-aged and the main species was hornbeam (*Carpinus betulus*) with the average stock of 240 m^3/ha. The area of the compartment was 65 ha and the existing road density of the studied district was 6.16 m/ha. Maximum and absolute gradient of the compartment were 69% and 20% to 50%, respectively. Cutting regime and silvicultural method were single or group selective cutting. The total volume of primary transportation which was carried out by skidders in short and long logs was 1330m^3. The landings were prepared at the border of road in the lower part of the compartment, and therefore the direction of skidding was entirely downward. The types of skidders used in this study were C450Timber Jack and Clark skidders. There were possibility to use both skidder in the area.

Data Collection

Time study data was collected in summer of 2009. In addition to the measurement of time for each work element, factors such as skidding distances, length and mean diameter of logs, gradient of skidding roads, winching distances, and number of logs in each skidding turn were also measured. In order to determine the number of required samples, first a preinventory was done to specify the time variance of skidding without considering delay time and then 30 cases of skidding were studied using the time study method. With the use of following formula the required samples with 95% confidence interval were 42 and 35 for Timber Jack and Clark skidders, respectively.

$$n = \frac{t^2 \times s^2}{E^2} \quad (1)$$

Where n is number of samples, t is t-student, s is standard deviation and E is standard error. References concerning to the time studies of forest harvesting operations indicate that the best way to create mathematical models of task performance time for harvesting machinery is variance analysis and multi-variable regression models. Minitab software was used and a mathematical model for skidding turn was developed. For estimating the machine rate, the FAO guideline (1980) was used. The skidding cost model was used to estimate the skidding cost for one cubic meter of wood extracted over different skidding distances.

Roads technical specification standard and method of wood extraction are two main factors that affect optimum road spacing of skidding operations. At the other hand, these factors affect optimum forest road network density, which is determined by minimum total cost (skidding and road construction costs), (Rowan, 1976). It is assumed that generally the roads are parallel and equal distance from each other. In fact these calculations are theoretical and are used as a general guide for explaining average skidding distance and skid trail borders. In practice forest road spacing can be determined with respect to different terrain conditions (Sedlak, 1981). Therefore, the actual skidding distances were measured in the studied area. These distances are included in calculations and based on this optimum road network density is determined.

Analysis of variance (ANOVA) is used to determine the relationship between dependent variable (total time) and independent variables in each work element and effective variables. In this analysis the first step is to make sure that the data are distributed normally and this is done by using normal plot and Anderson-Darling method. Then the relationship between time spent for work elements in each skidding turn and effective variables is specified with the use of scatter plot technique.

Linear Programming Model

Linear programming model was used in order to determine the minimum skidding cost of two skidders based on average skidding distances. In order to determine the optimum road network density, first of all the skidding cost for Timber Jack and Clark skidders costs per cubic meter of wood was calculated. Then the road construction was calculated. Finally, the linear programming model was used in order to reduce the skidding costs and to determine the optimal forest road network density.

RESULTS AND DISCUSSION

The relation between measured effective variables such as skidding distance, gradient, volume load and etc as well as their interaction with skidding time (skidding time without delay) are also determined and analyzed. The results show that the relation between variables and skidding time are mostly linear with different correlations. The stepwise regression is used to determine fixed coefficients. The model determined is as follows:

Mathematical equation of the skidding time as a function of effective factors

The following mathematical model was used to determine the skidding time of Timber Jack skidder:

$$Y=-3.75 + 1.71D +51.7V \quad (2)$$

Where: Y= time needed for one turn (minutes), V= load volume in (m^3), D= skidding distance (m)

Table. 1 shows the results of ANOVA test for Timber Jack skidder.

Table 1.Analysis variance of the model for Timber Jack skidder:

Source	SS	df	MS	*F*	R^2
Regression	13759223	2	6879613		
Residual	35101268	39	53138	12947	72.4% P<0.001
Total	18860493	41			

The following mathematical model also was used to determine the skidding time of Clark skidder:

$$Y=3.45 + 0.0268D +0.0018V \quad (3)$$

The results of ANOVA test for Clark skidder has been shown in Table 2.

Table 2. Analysis variance of the model for Clark skidder.

Source	SS	df	MS	*F*	R2
Regression	411.369	2	205.786		
Residual	89.100	32	4.050	50.786	82.4% P<0.001
Total	500.468	34			

The result of the study shows that the best model for skidding turns time is a function of independent variables such as volume per turn, skidding distance, winching distance and number of logs in each turn of skidding. Based on 99% confidence interval the model proved to be valid (Ttables1 and 2).

Two series of time-study information are randomly taken out from the data to be used in order to determine the model validity. Confidence limits of skidding time estimated by the model are calculated and compared with the real skidding time. The results show that the statistical validity of the model has been proved (Table.3).

Table 3: Validity of the model for Timber Jack and Clark skidder.

Kind of Skidder	Measured time	Estimated time
Timber Jack , first sample	19.13	21.02
Timber Jack , second sample	17.98	18.31
Clark, first sample	13.72	12.75
Clark, second sample	8.12	9.57

Production unit

In order to determine the production by two skidders, the following function was used.

$$P = \frac{V}{t} \quad (4)$$

Where as P is production (m^3/hour), V is wood skidded volume toward landing (m^3) and t is skidding operation time (hour).

The production for Timber Jack and Clark Skidders has been shown in Table 4.

Table 4. The production for Timber Jack and Clark Skidders.

Kind of Skidder	Production with delay time (m3/hour)	Production without delay time (m3/hour)
Timber Jack	11. 43	13.38
Clark	13.21	15.78

Skidding costs

In order to calculate the production cost over the location, FAO guideline manual is used (1980). Using this manual, the system costs consisting of machine costs simulation and labor costs are calculated and dividing these costs by the production over the location, production cost per cubic meter are calculated. Scheduled daily work hours were 8 hours and useful work hours were 6 hours per day. Then productivity is calculated based on a 6 hour day. The number of work days was considered 150 days per year. The results show that skidding costs without delay time is 8.41 \$/m^3 and with delay time is 9.44 \$/m^3 for Timber Jack skidder. The skidding costs for Clark skidder without delay time is 5.34 \$/m^3 and with delay time is 6.38 \$/m^3.

Skidding time prediction model was used to determine the skidding costs, the affect of variable changes on time is determined. Then by using skidding cost equation the skidding cost is determined for different skidding distances.

$$C = \frac{\frac{V \times [t \times Dt]}{v} \times Sc}{V} \quad (5)$$

C = Skidding cost (\$/m^3)
V = Total volume of skidded wood (m^3)
t = Time per skidding turn (hour)
Dt = Average delay time (hour)
Sc = System cost (machinery and labor costs) (\$/hour)
v = Average volume of skidded wood in one turn (m^3)

Therefore, the effect of skidding distance changes on skidding cost can be studied using the equation above. In order to determine the skidding cost for each different forest road network density, first of all the skidding distances relevant to different road density is determined. Then with the use of skidding cost equation (5) and considering the relation between skidding distance and skidding costs, the skidding costs for different skidding distances and for different road density is calculated.

Skidding trail construction cost

In order to determine the skidding trail construction cost, first of all the length of skidding trail per hectare has been calculated based on the following function:

$$d = \frac{D}{S} = \frac{3422}{65} = 52.6\text{m/ha} \quad (6)$$

d is the length of skidding trail per hectare (m/ha.) , D is the total length of skidding trail(m), S is compartment area (ha.).

Annual forest growth is 4m³/ha. For 10 years period (in single selection method), the forest growth is 40 m³/ha.The skid trails

construction cost is 1100$/km, this is the cost for excavation, earth filling and preparing the skid trails (Shafarood Forest Cooperation, 2009). Therefore, for 52.6m is 57.9$. This is the cost for 40m³ of wood. Hence the skidding cost per cubic meter is 57.9/40=1.45$/m³.Consequently the skid trails construction cost (1.45$/m³) is added to skidding cost to obtain final skidding cost for Timber Jack and Clark skidders (Figure 1).

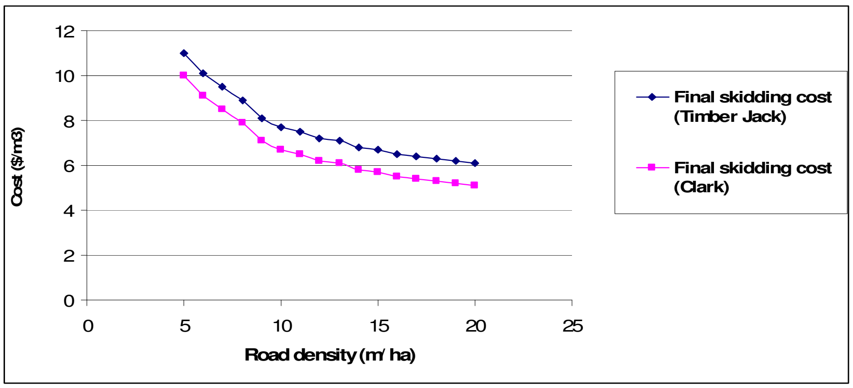

Fig 1. Relation between road density and final skidding cost of two skidders.

Road network density and road construction costs

Road construction costs

The road construction costs include excavation and filling (construction of trails by bulldozer), pavement and finishing and retaining wall and drainage construction costs. The planning costs of forest road project are taken as 10% of these costs (Table 5), (Shafarood forest cooperation. (2009).

Forest road cost

Annual forest road cost per km determined by total cost of capital interest, depreciation and repair, and maintenance costs (Table 5).

Table 5. Road construction and planning costs in the studied area

Type of cost	Cost ($/km)
Excavation and filling	5817
Pavement and finishing	8370
Retaining wall and drainage construction	6332
Planning	2052
Total	22571

Capital interest

Annual capital interest could be determined by $r = iR$, where as, i =16.5%, R = Average capital value ($) and r is annual capital interest.

According to the data, r can be calculated like:

$$r = \frac{22571}{2} = 11285 \rightarrow 11285 \times 0.165 = 1862\$/\text{km}$$

Depreciation

Annual depreciation cost is calculated as below:

$$\text{D} = \frac{\text{Cost (\$/Km)}}{\text{Useful life(year)}} = \frac{22571}{50} = 451\$/km$$

Repair and maintenance cost

Repair and maintenance cost of road is 5% of road construction cost.

Annual repair and maintenance cost = 20519×0.05=1026$/km

Restoration cost

Road restoration cost for 20 years is 30% of capital cost. Therefore annual restoration cost is 1.5% of capital cost.

Annual restoration cost = 20519×0.015=308$/km.

Summing up the above mentioned costs, the annual road construction cost was 3647$/km.

Therefore, for forest road network density of 5m/ha and forest growth of 4m^3/ha (in single selection method) the road construction cost is 4.56 \$/m^3. Consequently the road construction cost is added to final skidding cost (skidding cost and skid trail construction cost) to obtain total cost.

The optimum road network density may be determined with the help of total costs curve which is composed to the road and skidding costs. This limit is at the lowest level of the total costs curve. The results shows that suitable forest road network density in the studied area respect to road and skidding costs, is in the range of 7-9 m/ha.

Linear programming Model

Skidding cost of Timber jack and Clark skidders has been studied. It was interesting to choose the best skidder and average skidding distance in order to reduce the skidding costs. Hence, linear programming model was used in order to reduce the skidding costs and to determine the optimal forest density. The question is how much log each skidder in each skid trail should extract to minimize the skidding cost.

The linear programming model could be written as:

$$\min Z = \sum_{i\in I}\sum_{j\in J} C_{ij} X_{ij} \qquad (7)$$

Subject to

$$\sum_{i\in I}\sum_{j\in J} X_{ij} = \sum_{i\in I} V_i \qquad (8)$$

$$\sum_{i\in I}\sum_{j\in J} t_{ij} X_{ij} \le \sum_{j\in J} T_j \qquad (9)$$

$$\sum_{i\in I}\sum_{j\in J} X_{ij} \ge 0 \qquad (10)$$

I is the number of average skidding distance according to the forest road network density, here we have chosen 3 average skidding distance those conforming to the proposed forest network density (7-9 m/ha).

J is the number of skidders, , here we have 2 kind of skidders, Timber Jack and Clark.

V_i is the total allowable cut on the trail i.

C_{ij} is skidding costs ($\$/m^3$) on the average skidding distance i extracted by skidder j.

t_{ij} Logging time of skidder j on the average skidding distance i.

$\sum_{j\in J} T_j$ time (minute) allocated for skidder j by company.

Equation (7) is the objective function. It is subject to minimizing the total skidding cost which by itself is subject to 3 types of constraints.

The first constrain or Equation (8) shows that the total allowable cut is equal to the sum of allowable cuts per hectare. Here the annual forest growth is 4m^3/ha. For a 10 year long period (in single selection method), the forest growth is 40 m^3/ha. Hence in our model, the total allowable cut is 40 4m^3/ha.

The second constraint (Equation 9) shows that total skidding time of each skidder should not be more than total allowed time. According to the Equation (4), we can determine the average extracted volume or production of each skidder for one turn. The average extracted volume was determined 4 m^3. Based on Equation (2 and 3) it is possible to calculate the average skidding time. Here, it was calculated 20 minutes. Hence, the total allowable skidding time could be calculated 200 minute to extract 40 m^3 of logs. Linear programming model has been solved. The results show that in order to reduce the skidding costs, it is better to extract 27.5 m^3 of logs at skid distance of 562 m and 12.5 m^3 of logs by skid distance of 500 m by Clark skidder (Table 6). If we compare the average skid trail distances to the road network density, the optimal road density could be about 8 meter per hectare.

Table 6. Summary of the linear programming solution.

Skidders	Average skidding distance (m)	Road density (m/ha)	Variable name	Final value (m3)	Objective coefficient (Final skidding cost, \$/m3)
Timber Jack	643	7	X11	0	9.92
Timber Jack	562	8	X12	0	9.34
Timber Jack	500	9	X13	0	8.93
Clark	643	7	X21	0	8.9
Clark	562	8	X22	27.5	8.25
Clark	500	9	X23	12.5	8

Conclusions

The aim of this research was to calculate skidding and road construction costs, in order to determine the optimum forest road network density. The mathematical model was used in order to predict the skidding time. Furthermore, the average skidding distances were determined for different road density. Then, the skidding cost for different skidding distances was calculated. Annual road construction cost was determined per cubic meter of wood extracted from forest roads. The sum of road construction and skidding costs for different road density were determined. Based on minimizing these two costs, the proposed forest road network density could be 7 to 10m/ha. Linear programming model was used in order to reduce the skidding costs and to determine the optimal forest road network density. The results show that in order to reduce the skidding costs, it is better to extract 27.5 m^3 of logs at skid distance of 562 m and 12.5 m^3 of logs by skid distance of 500 m by Clark skidder. This is in correspondence with 8 meter of road density per hectare.

The results of researches carried out in Iranian Caspian showed that optimal road density ranged from 6 to 28 m/ha for different areas (Feghi 1990; Mostafanejad, 1995; Naghdi, 2004; Naghdi and et al. 2005 and Eghtesadi, 1991; eghtesadi, 2000, Ghaffarian and Sobhani, 2008). This study is similar to the results of previous studied. The privilege of this research is that we have used linear programming to determine the best skidder and optimal road density. The existing road density in the study district is so high and it's 16 meter per hectare which increase highly the total cost per cubic meter. Therefore, it is necessary to apply the optimum road density for opening the other districts of Iranian Caspian forest to minimize the total forest harvesting cost.

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