Economics of a hydraulic hammer for forest road construction in a mountainous area

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ABSTRACT: This research deals with productivity and cost of rock disintegration and side casting of materials with the use of a hydraulic hammer mounted on a PC 220 Komatsu crawler excavator, which is used on rocky slopes of Hyrcanian forests of Iran. A continuing time study was applied during the road construction. To estimate the volume of rock disintegration, the average end area equation was used. The increasing cut-slope height decreased productivity. The productivity of hydraulic hammer averaged at 5.5 $m^3 \cdot h^{-1}$ for the mean work volume of 5.07 $m^3 \cdot m^{-1}$. The unit cost of the system was 7.7 €·m^{-3}. From the economic point of view a new machine with multipurpose system could be recommended for forest road construction operations in rocky areas.

Keywords: hydraulic hammer; rock disintegration; cut slope; productivity; costs

The construction of forest roads for Iranian forestry began in 1959. The technical office of forest organization reported that the total length of forest roads in the Hyrcanian region was 10,000 km at the end of 2009. Besides, the mean density of these roads was 11 $m \cdot ha^{-1}$ (Parsakhoo et al. 2008). Planning and building of the road network are performed according to principles of Bulletin No. 131 and 148, published by the Plan and Budget Organization of Iran (PBOI). According to the guidelines of the Iranian Forest Service, a hydraulic excavator must be used for building forest roads in steep terrains of the slope more than 50%. Overall, in mountain regions of the Hyrcanian forests, road building is difficult due to larger quantities of stones and rocks. In previous years, rock disintegration was frequently performed by traditional methods such as Dynamite and Cardox. Nowadays, non-explosive demolition agents such as expansive chemical substances, rock cracker, hydraulic excavator and hydraulic hammer are used to disintegrate stones (Parsakhoo, Lotfalian 2009).

Hydraulic hammer is a noisy tool causing an occupational health hazard in the construction industry (Sedlak 1996; Winkler 1998). Many factors such as slope (gradient, length, shape, and position on the slope), geologic factors (rock type, strength and hardness, bedding planes, faulting, and subsurface drainage) and climate can affect the productivity of hydraulic hammer and other excavation machines (Mitin et al. 1975; Turnbull et al. 1992). The appropriate type of hammer can be selected out of a hammer series with operating weights ranging from 150 to 3,500 kg for all types of carrier units ranging from 1.5 to 80 t (Vasilev, Goncharov 1997).

Filipsson and Eriksson (1989) determined the quantity of 11.3 $m \cdot h^{-1}$ with standard deviation 4.2 m for a Hitachi 121 LC hydraulic excavator in the stony terrain of Sweden forests. Other productivity studies resulted in the range of 2.42 to 5.69 $m \cdot h^{-1}$, depending on the machine type and working conditions. Moreover, it has been reported that the production costs of the hydraulic excavator system in the stony and rocky terrain are in the range of 10 to over 17 USD·h^{-1} (IUFRO 1995). In another research project in the rocky terrain, the estimated costs of road construction

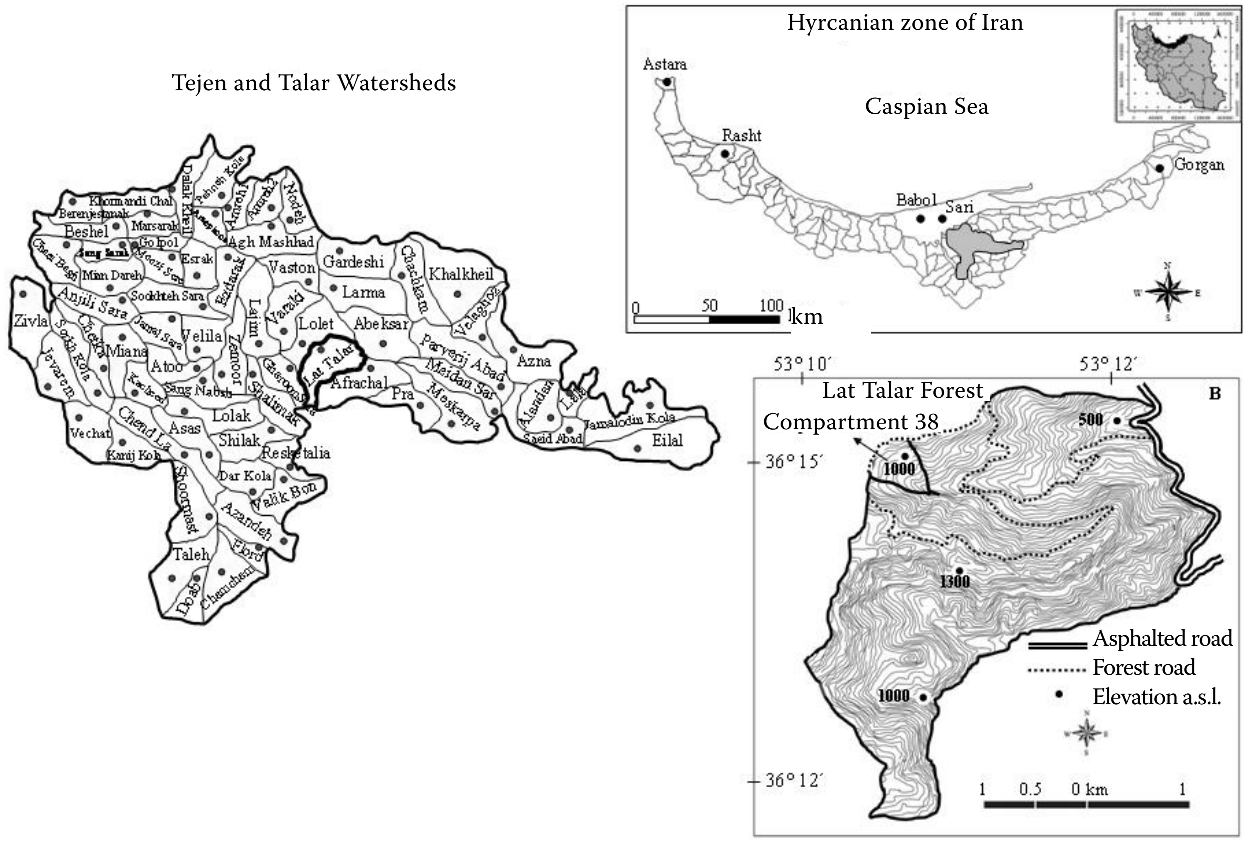

Fig. 1. Location of the Lat Talar Forest

works by hydraulic hammer were 0.15 USD·m^{-1} and 1.80 USD·m^{-1} (FAO 1992).

Where rock surfaces are to be crossed, final shaping of the cut slope and establishment of the ditch will be provided by means of a hydraulic hammer attached to the excavator (Voitsekhovskaya 1985). Hydraulic hammers therefore make an excavator even more versatile and cost effective as no drilling equipment and explosives are needed to break out pockets of rocks and alterations in the road location can be avoided (Sessions 2007), but research on the hammer productivity has been very limited in Iran. So, the objective of this research is to determine the efficiency and costs of rock disintegrating by the hydraulic hammer mounted on a crawler excavator.

MATERIAL AND METHODS

Study area

Lat Talar Forest in watershed number 71 in the Hyrcanian zone of Iran was selected as the study area (Fig. 1). The location of the research is 36°15'45"N, 53°10'40"E, 1,000 m above sea level. The region has a mid-moist and cold climate with the mean annual precipitation of 635 mm. The bedrock is typically marl, marl lime and limestone with the soil texture of loam and clay loam. Forest stands are dominated by *Fagus orientalis* Lipsky and herbaceous species *Carex sylvatica*, *Buxus hyrcanus*, *Brachypodium sylvaticum*, *Ruscus hyrcanu*s, *Phyllitis scolopendrium* and *Polypodium auidinum* (Table 1).

Table 1. Technical data of the constructed area in compartment 38

Ground slope (%)	90–110
Litter thickness (cm)	5–10
Soil depth (cm)	25–30
Cut-slope height (m)	2.5–4.0
Cut-slope width (m)	2.5–3.0
Cut-slope angle (degree)	80–85
Road width (m)	4.0–4.6
Fill-slope length (m)	25–50
Fill-slope width (m)	1.0–1.5

Fig. 2. Hydraulic hammer mounted to PC 220 Komatsu crawler excavator

Fig. 3. Rock disintegration by hydraulic hammer

Fig. 4. Side casting of stones by hydraulic hammer

Road construction in study area

Fig. 2 illustrates a hydraulic hammer mounted on a Komatsu excavator. Moreover, the drilling operation by a hydraulic hammer can be seen in Fig. 3. After drilling and disintegrating of the rock, the side casting of disintegrated stones is done by a hydraulic hammer (Fig. 4).

Data collection

A segment of road was under construction by a hydraulic hammer of the PC 220 crawler Komatsu excavator in compartment 38 of Lat Talar Forest (Table 2). All trees within the right of way were felled before the rock disintegration operation started. The degree of stone hardness was measured using the Mohs scale.

The elements of the machine daily work were measured with a digital stop watch and video camera. The productive time per day and working delays were recorded in the time study. Besides, non-effective time is the other part of utilized time that includes relocation time, delays time, service time and preparatory time (Björheden 1991). Cost calculations were based on the methods used by FAO.

The productivity of the hydraulic hammer of the PC 220 crawler Komatsu excavator was determined on the basis of the measured daily volume of rock

Table 2. Technical features of hydraulic hammer and PC 220 crawler Komatsu excavator

Weight of hydraulic excavator (t)	24
Age of hydraulic excavator (year)	2
Engine type of hydraulic excavator	Komatsu SAA6D107E-1 ecot 3
Engine power of hydraulic excavator (kw)	134
Speed of hydraulic excavator (km·h^{-1})	3.1–5.5
Drill diameter of hydraulic hammer (cm)	13.5
Drill length of hydraulic hammer (cm)	55
Length of hydraulic hammer (cm)	175
Operator experience (year)	5
Boom length (m)	7
Bucket breakout force (kg·f^{-1})	17,500
Arm breakout force (kg·f^{-1})	13,200
Track pad width (cm)	60
Track length (cm)	420
Gradeability (%)	70

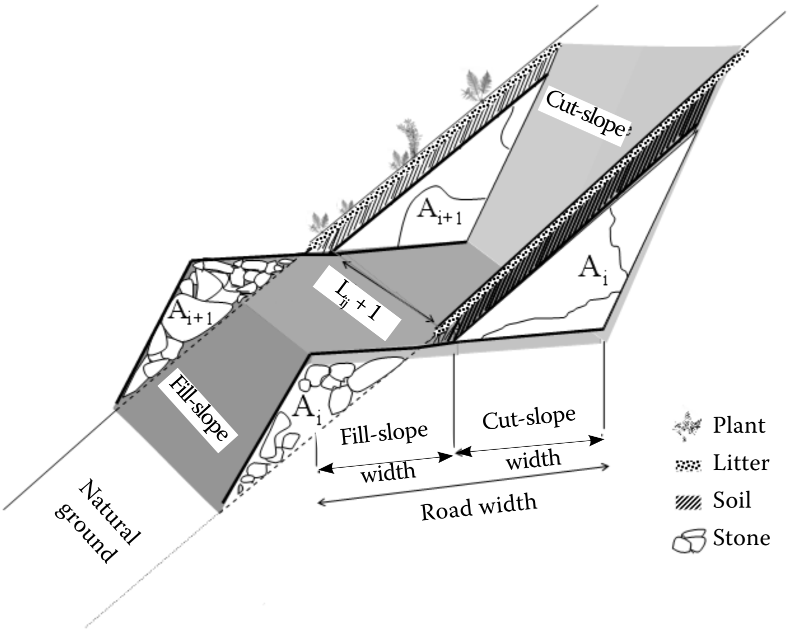

Fig. 5. Schematic illustration of the cross-section of terrain and road in the study area

disintegration by a hydraulic hammer. For this purpose, cross-sections of the terrain and road were taken every 2 m using a tape and clinometer. The cross-sections were later plotted and their areas were calculated. To estimate the volume of rock disintegration, the average end area equation was used (Abeli 1993):

$$V_{i,\,i+l} = 0.5(A_i + A_{i+1})L_{i,\,i+l} \qquad (1)$$

where:

$V_{i,\,i+1}$ – volume of rock disintegration between the i^{th} section and the $i+1$ section (m^3),

A_i, A_{i+1} – area of the i^{th} cross-section and the $i+1$ section (m^2),

$L_{i,\,i+1}$ – distance between the road section i and the section $i+1$ (m) (Fig. 5).

Average fuel consumption ($l \cdot h^{-1}$) was measured using a fuel meter previously installed on the hydraulic excavator by the producer company. Moreover, the daily consumption of fuel was controlled by a fuelling machine at the end of the working time.

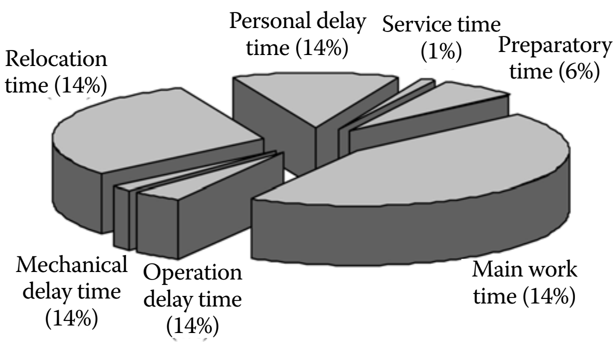

Fig. 6. Structure of time consumptions in the study area

RESULTS

From the time study, only 49% of the total time was productive and the proportion of non-productive time was about 51% of the total recorded time. According to the definitions of basic time concepts by Björheden (1991), the average main work time at the study area was 43%. The share of relocation time in total utilized time was 30%. Daily components of the time study are shown in Fig. 6.

In the case of a cut slope of 2.5 m in height, the hydraulic hammer productivity value was 5.57 $m^3 \cdot h^{-1}$ for the rock disintegrating operation and 2.13 $m^3 \cdot h^{-1}$ for earth working. Moreover, as for rock disintegra-

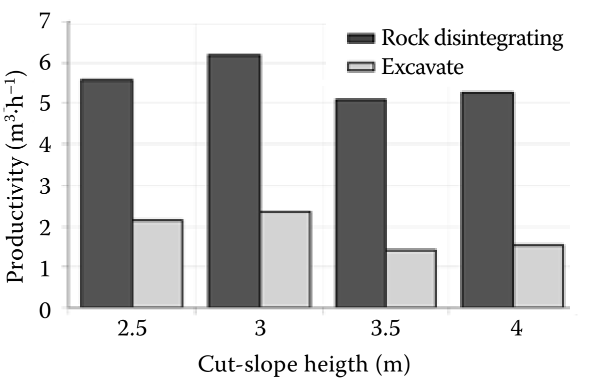

Fig. 7. Productivity of hydraulic hammer in different cut slope heights

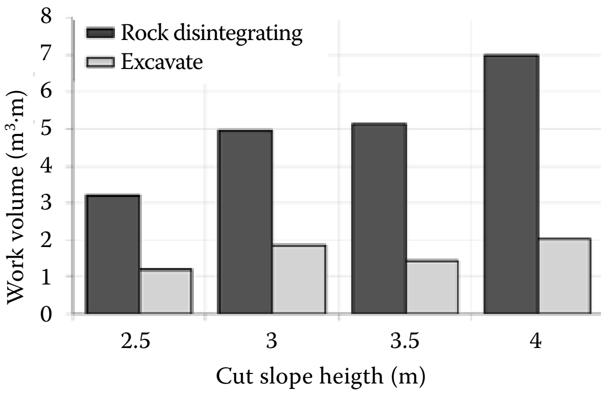

Fig. 8. Work volume of hydraulic hammer in different cut slope heights

tion carried out by a hydraulic hammer, the productivity values for the cut-slope height of 3 m, 3.5 m and 4 m have been determined as 6.18 $m^3 \cdot h^{-1}$, 5.11 $m^3 \cdot h^{-1}$ and 5.24 $m^3 \cdot h^{-1}$, respectively (Fig. 7).

The average work volume of rock disintegration for the cut slope height of 4 m was 7 $m^3 \cdot m^{-1}$. The average work volume for the cut slope height of 2.5 m, 3 m and 3.5 m was 3.19 $m^3 \cdot m^{-1}$, 4.96 $m^3 \cdot m^{-1}$ and 5.12 $m^3 \cdot m^{-1}$, respectively (Fig. 8).

It was assumed in a regression analysis that the production of the excavator was a function of road width (Fig. 9) and cut-slope height (Fig. 10). However, there was a significant correlation between these variables based on the Pearson correlation test. The coefficient of correlation was about 0.93. This collinearity did not allow us to develop a multiple regression including both variables. Thus an interaction of these variables (road width × cut-slope height) was applied to fit a curve estimation model in SPSS 17 (Fig. 11).

$$\text{Productivity (m/day)} = -7.959 \ln (\text{road width (m)} \times \text{cut-slope height (m)}) + 25.736$$

$n = 16$, $R^2 = 0.93$

The R^2 of 0.93 indicates that 93% of the variations of dependent variables can be explained by the model. The significance level of the ANOVA table (Table 3) confirmed that the model makes sense at the probability level of 95%. The table of coefficients (Table 4) presents the significance level of including the variable and constant coefficient.

Fuel consumption is an indicator of the hydraulic hammer productivity. The fuel consumption to construct each meter of the road in our study area was 16.95 l (Table 5). The cost elements of

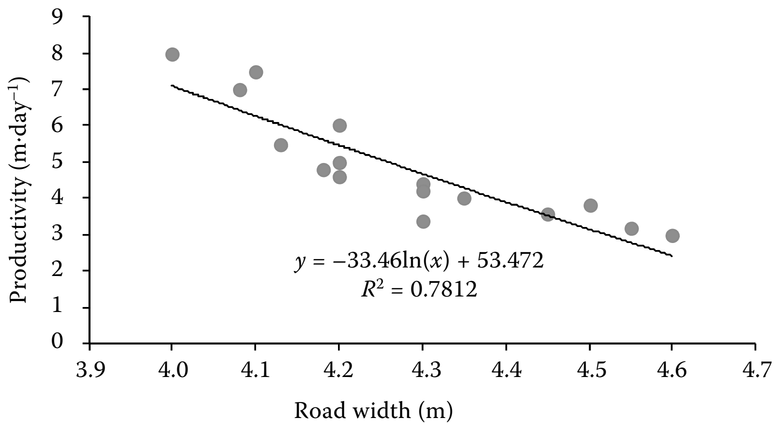

Fig. 9. Productivity of hydraulic hammer versus road width

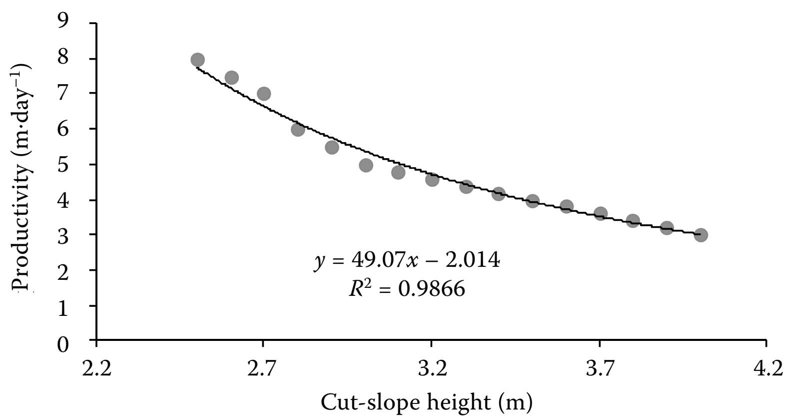

Fig. 10. Productivity of hydraulic hammer versus cut-slope height

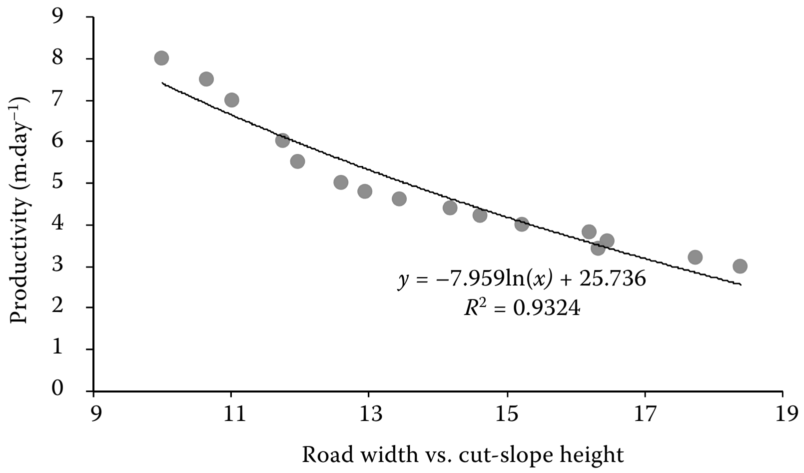

Fig. 11. Productivity of hydraulic hammer versus cut slope height and road width

the hydraulic excavator plus hydraulic hammer during rock disintegrating and side casting at different heights of cut slopes are shown in Table 6. Maintenance and repair are defined as all activities which are carried out with the aim of maintaining a system in the technical state necessary for the system to perform properly in respect of the type and extent of its designated functions (Balcom 1988). In this study, hourly maintenance and repair cost was 4.1 EUR. Total hourly cost of the system was 42.5 EUR. The unit cost of the system was 7.7 EUR·m^{-3}. Fixed cost of the system is divided into depreciation cost, interest, garage, insurance and taxes costs. The fixed cost of the system accounts for 40% of total cost, and running cost for 12%. The transportation cost of the system is 3%, and labour cost 27%. The hydraulic hammer cost accounts for 18% of the total cost of the system (Fig. 12).

DISCUSSION

Previous studies in Tanzania indicated that the mean unit costs for the D6, D4 and county tractor were 0.712 EUR·m^{-3}, 1.150 EUR·m^{-3} and 1.110 EUR per m^{-3}, respectively (Abeli 1993). Besides, in Canada the unit costs of earthworking operations were 0.672 EUR·m^{-3}, 0.642 EUR·m^{-3} and 1.387 EUR·m^{-3} for D8 Caterpillar bulldozer, 235 hydraulic backhoe and hydraulic shovel, respectively (Nagy 1978). The average unit cost was found to amount to 7.7 EUR·m^{-3} in this study.

Table 3. ANOVA of productivity model

	Sum of squares	Degree of freedom	Mean square	F	Significance
Regression	33.24	1	33.24	193.121	< 0.0001
Residual	2.41	14	0.172		
Total	35.65	15			

Table 4. Coefficients of productivity model

	Unstandardized coefficients		Standardized coefficients	t	Significance
	B	Std. error	Beta		
Ln (width slope)	–7.959	0.573	–0.966	–13.897	< 0.0001
Constant	25.736	1.505		17.104	< 0.0001

Table 5. Fuel consumption in study area

Production (m^3·h^{-1})	Production (m·h^{-1})	Fuel consumption (l·h^{-1})	Fuel consumption (l·m^{-1})	Fuel consumption (l·m^{-3})	Fuel cost (EUR·m^{-1})
5.52	1.18	20	16.95	3.62	0.25

Table 6. System costing in EUR based on 2008 prices

Delivered price (EUR)	153,846.1
Depreciation period (year)	30
Annual usage (h)	1,250
Salvage value (10%)	15,384.6
Average annual investment (EUR)	86,923
Machine fixed cost	
Depreciation cost ($EUR \cdot h^{-1}$)	3.7
Interest: 18.5% AAI ($EUR \cdot h^{-1}$)	12.9
Insurance & taxes ($EUR \cdot h^{-1}$)	0.4
Machine running cost	
Maintenance & repair ($EUR \cdot h^{-1}$)	4.1
Fuel cost ($EUR \cdot h^{-1}$)	0.3
Oil and lubricants ($EUR \cdot h^{-1}$)	0.7
Labor (driver and assistant) ($EUR \cdot h^{-1}$)	11.3
Hydraulic hammer ($EUR \cdot h^{-1}$)	7.7
Transportation cost ($EUR \cdot h^{-1}$)	1.4
Total cost	
Hourly cost of system (EUR)	42.5
Productivity of hydraulic hammer ($m^3 \cdot h^{-1}$)	5.5
Productivity of hydraulic hammer ($m \cdot day^{-1}$)	4.9
Unit cost ($EUR \cdot m^{-3}$)	7.7
Utilized coefficient (%)	50.3

In this study, the average productivity of hydraulic hammer was found to be 5.5 $m^3 \cdot h^{-1}$, with the work volume of 5.07 $m^3 \cdot m^{-1}$. The productivity of hydraulic hammer averaged at 1.18 $m \cdot h^{-1}$. In a study conducted by Filipsson and Eriksson (1989) in the stony terrain of Sweden forest, the productivity of Hitachi 121 LC hydraulic excavator was 11.3 $m \cdot h^{-1}$. The difference in productivity was caused by a smaller rock size in the Swedish study.

It was observed that both disintegrating and side casting operations were performed by a hydraulic hammer. Hydraulic hammer productivity in these operations was higher compared to the past studies (Mitin et al. 1975). Since the excavator had not a bucket to control the side-cast materials, there was not any delay time for mounting and dismounting the bucket. The bucket of hydraulic excavators can place the material more precisely than the hammer, so the bucket will lose less material. Different available types of buckets enable the excavator to carry out specific construction works and ensure the highest performance (Sessions 2007). Furthermore, the operator in the present research was 26 years old with 5-year work experience on heavy equipment, while younger operators tend to work faster because they are more energetic compared to older operators (Fue et al. 1996).

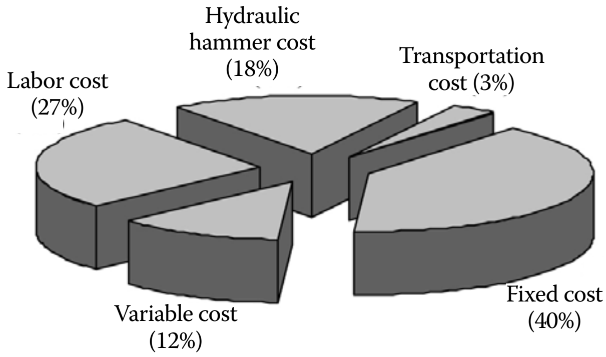

Fig. 12. Total cost elements

In this study the fixed cost of the system accounts for 40% of total cost, and the variable cost for 12%. The overall average utilization of the hydraulic hammer was 50.3%. Delays are recognized as being among the major factors that limit the hydraulic hammer productivity in most operations and are therefore an integral part of most time studies. In the present study, delay time was divided into operational delay, personal delay and mechanical delay (Spinelli, Visser 2009).

Two thirds of the total delay time are represented by personal delays, which emphasizes the crucial role of permanent supervision on labour performance. The utilization of the hydraulic hammer could have been greatly increased if resting and eating related delays could have been avoided. These delays were the highest for the system. Overall, mechanical delays did not greatly reduce the production for the system studied. The hourly cost of hydraulic hammer can be minimized by the adequate planning of disintegrating and side casting operations to reduce relocation time and delays such as frequent intermediate stops of the operator to rest. In addition, mechanical delays can be reduced through the regular servicing of equipment (Sowa et al. 2007). The increase of productivity can be obtained by providing daily food requirements in time (Adebayo 2006). The low productivity of hydraulic hammer causes high production costs. Moreover, geometrical characteristics of the excavator such as comfort of the cab layout and seat, location of controls and the operator's body position are parameters which can affect the system productivity (Gerasimov, Sokolov 2009).

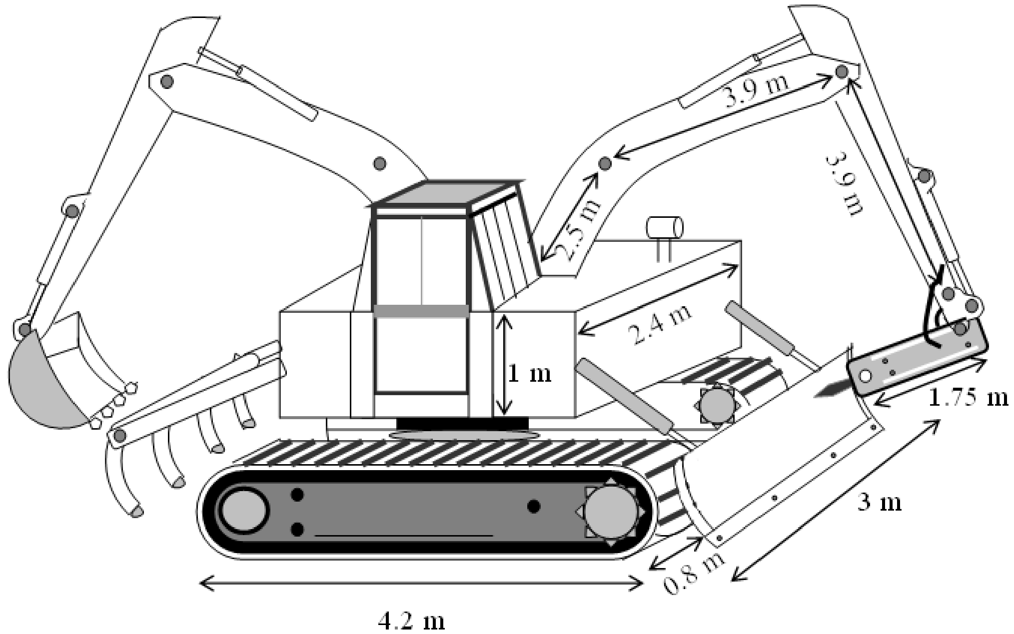

Fig. 13. Suggested design of a combined machine (hydraulic excavator and bulldozer)

CONCLUSION

From the results of this study, productivity and cost of Komatsu hammer averaged at 5.5 $m^3 \cdot h^{-1}$ and 7.7 $EUR \cdot m^{-3}$ respectively. Moreover, the productivity of hydraulic hammer was affected by cut slope height and road width. The next research can investigate a combined excavator-hammer in order to improve the productivity of road construction (Fig. 13). Also more studies need to be carried out in different slopes, soils and degrees of stone hardness.

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