








MODELING OF TECHNICAL, ECONOMIC, ENVIRONMENTAL AND ERGONOMIC PARAMETERS OF FORESTRY MACHINES IN FUNCTION OF THE QUANTITY OF DAYS OF THE WORKING SCALE

Diego Weslly Ferreira do Nascimento Santos*¹ , Marconi Ribeiro Furtado Junior² , Juliana Pinheiro Dadalto³ , Larissa Nunes do Santos²  & Daniel Mariano Leite⁴ 

1 - Federal University of Lavras

2 - Federal University of Viçosa

3 - Rural Federal University of Pernambuco

4 - Federal University of San Francisco Valley

Keywords:

Forest harvesting
Forest ergonomics
Agricultural mechanization

ABSTRACT

Forest machine operators work on a long scale of work, which causes physical and psychological wear and consequently reduced productivity and increased fuel consumption. The objective of this research was to verify the influence of the number of days of the work schedule of harvester and forwarder operators in low-volume forest on technical, economic, environmental and ergonomic parameters. The research was performed in forest stands with an average wood volume of 0.10 m³ tree⁻¹. In the first, second, third and fourth day of the work schedule, productivity, energy demand, production cost, carbon dioxide emission and the occurrence of fatigue in the operators were determined. The productivity values of harvester operators on the third and fourth days of the work schedule decreased by 2.62 and 7.74%, respectively, in relation to the average value of the first and second days. The productivity of forwarder operators was similar in the first three days of the work schedule, with a more marked reduction in the fourth day. The reduction in the number of days in the forest machine operators' work schedule makes the operation more sustainable from a technical, economic, environmental and ergonomic point of view.

Palavras-chave:

Colheita florestal
Ergonomia florestal
Mecanização agrícola

MODELAGEM DE PARÂMETROS TÉCNICOS, ECONÔMICOS, AMBIENTAIS E ERGONÔMICOS DE MÁQUINAS FLORESTAIS EM FUNÇÃO DA QUANTIDADE DE DIAS DA ESCALA DE TRABALHO

RESUMO

Operadores de máquinas florestais trabalham por longas escala de trabalho, o que proporciona desgaste físico e psicológico e conseqüentemente redução de produtividade e aumento do consumo de combustível. Objetivou-se com a presente pesquisa verificar a influência da quantidade de dias da escala de trabalho de operadores de harvester e forwarder em floresta de baixo volume sobre parâmetros técnicos, econômicos, ambientais e ergonômicos. A pesquisa foi realizada em povoamento florestal com volume médio da madeira de 0,10 m³ árvore⁻¹. No primeiro, segundo, terceiro e quarto dia da escala de trabalho foi determinada a produtividade, demanda energética, custo de produção, emissão de dióxido de carbono e ocorrência de fadiga nos operadores. Os valores de produtividade dos operadores de harvester no terceiro e quarto dia da escala de trabalho reduziram 2,62 e 7,74%, respectivamente, em relação ao valor médio do primeiro e segundo dia. A produtividade dos operadores de forwarder foi semelhante nos três primeiros dias da escala de trabalho, com redução mais acentuada no quarto dia. A redução da quantidade de dias da escala de trabalho de operadores de máquinas florestais torna a operação mais sustentável do ponto de vista técnico, econômico, ambiental e ergonômico.

INTRODUCTION

The forest harvesting system composed of harvester and forwarder is used extensively in Brazil. Such machines make it possible to harvest large areas in a short time and provide good ergonomic conditions to operators, when compared to a semi-mechanized and manual system. However, operators are susceptible to the occurrence of RSI/WRMD (Repetitive Strain Injuries / Work-Related Musculoskeletal Disorders), due to performing repetitive movements, maintaining an asymmetrical position for long periods and working long hours (SILVA *et al.*, 2013).

Forestry companies adopt different scale systems, the size of which varies according to the intrinsic characteristics of the companies. Long work schedules reduce productivity and subject operators to the occurrence of RSI / WRMSD, requiring pauses to alleviate symptoms (SILVA *et al.*, 2014). For this reason, the number of days of work schedules must be planned according to ergonomic criteria, so that it does not cause occupational diseases and provides economic and environmental gains.

In recent years, efforts have been made to increase the efficiency of wood harvesting equipment and to reduce pollutants emitted by diesel engines that affect human health and the environment (PETRANOVIC *et al.*, 2015). As a result, new technologies are tested on forest machines, such as hybrid engines and renewable fuels (BIETRESATO *et al.*, 2019). However, they are solutions for the near future, requiring immediate measures to be taken to increase the energy efficiency of forest machines.

Increasing productivity and reducing hourly fuel consumption promote significant gains in the energy efficiency of forest machines (SANTOS *et al.*, 2020a). However, as reported by Silva *et al.* (2013), forest machine operators work over long work scales and in a target system, which provides physical and psychological wear and consequently reduced productivity and increased fuel consumption.

Thus, the present research aimed to evaluate the influence of the number of days of the work schedule on technical, economic, environmental and ergonomic parameters of harvester and forwarder operators operating in low volume forests.

MATERIAL AND METHODS

The research was performed in Nova Viçosa, Bahia, Brazil. The region has a Humid Tropical Climate (Af) with an average annual temperature of 24.4 °C and an average annual rainfall of 1,350 mm. Data collection was performed between the months of January to May 2019. Data collection was performed in areas populated with hybrid clones of *Eucalyptus grandis* x *Eucalyptus urophylla*, planted at a distance of four meters between rows and 2.5 meters between plants. The trees were harvested at an average age of 6.3 years.

The research was conducted on a 4x2 work schedule system, with four days of continuous work and two days off. Data collection started at 6:00 am and ended at 3:00 pm. Data were collected from twelve operators, with an average age of 35 years and an average time worked in the company for 5 years. A cut-to-length forest harvesting system consisting of harvester and forwarder machines was used. The harvester was responsible for cutting, uncapping, delimiting, peeling, sectioning and stacking the logs while the forwarder performed the extraction of the wood from the interior of the plots to the margins of the roads.

The harvester machine used was composed of a hydraulic excavator (model PC200F-8M0, Komatsu); track wheels; diesel engine (model SAA6D107E-1, Komatsu), with six cylinders and 110 kW of nominal power at 2060 rpm and the head (model 370E, Komatsu). The forwarder machine used was model 895 with eight-wheel drive (Komatsu). The machine was equipped with the AGCO diesel engine, 74CW3 model power, with 6 cylinders and 193 kW of nominal power at 1,950 rpm. The cargo box had a capacity of 23 cubic meters of wood.

The research was performed in forest stands with an average volume of 0.10 m³ tree⁻¹, considered as low. On each day of the work schedule, 24 experimental plots were marked for each machine, using simple casual sampling. In the plots, information was collected to determine productivity, energy demand, production cost, carbon dioxide emission and the occurrence of fatigue in operators.

The amount of fuel consumed for time spent in each experimental plot was measured using a flow meter installed in the harvester and forwarder fuel supply system. The FLOWMATE M-III® flow meter, model LSF41C, was used. Together with the flow meter, a graphic display (indicator), model LCT (TechMeter), was installed. Subsequently, the amount consumed per parcel was transformed into hourly fuel consumption using equation 1.

$$Hc = \frac{Q}{T} \cdot 3.6 \quad (1)$$

Where,

Hc = Hourly fuel consumption (l h⁻¹);

Q = Amount of fuel consumed in the plot (mL); and

T = Time spent on the plot (s)

Productivity (m³ h⁻¹) was calculated using the quotient between the volume of wood present in the plot (m³) and the time spent in that plot (h). Energy demand was determined by dividing hourly fuel consumption (l h⁻¹) and productivity (m³ h⁻¹). The production cost (US\$ m⁻³) was calculated from the quotient between the operating cost (US\$ h⁻¹) and the productivity of the machines. The operating cost was determined by adding the fixed and variable costs according to the methodology proposed by Miyata (1980). With regard to fixed costs, the cost of depreciation, interest, insurance, security, administrative personnel, operator's salary and cost of maintenance personnel were determined. The variable cost was calculated considering the cost of fuel, hydraulic oil, lubricating oil, grease, chain oil, spare parts and organization of the module area. An exchange rate of US\$ 1 = R\$ 5.36

was used, quoted on 08/06/2020. The amount of carbon dioxide (CO_{2eq}) emitted by harvester and forwarder machines was measured using equation 2, according to the methodology proposed by Santos *et al.* (2020a).

$$CO_{2eq} = \frac{EF \ Hc \ Cpp}{Pr} \quad (2)$$

Where,

CO_{2eq} = Carbon dioxide (kg m⁻³);

EF = Emission factor (kg TJ⁻¹);

Hc = Hourly fuel consumption (kg h⁻¹);

Cpp = Calorific power (TJ kg⁻¹); and

Pr = Productivity (m³ h⁻¹).

The occurrence of fatigue in the harvester and forwarder operators in the four days of the workday was analyzed using the Bipolar questionnaire, according to the methodology proposed by Couto (2012). The operators answered the questionnaire at the beginning, middle and end of the workday. The order of the questions was changed in each period, in order to avoid results manipulation.

The data were analyzed using simple regression, with the independent variable being the days of the workday (1°; 2°; 3°; and 4°) and the dependent variables being productivity, energy demand, production cost and carbon dioxide. The models were selected based on the coefficient of determination, behavior of the phenomenon under study and the significance of the regression coefficients, using the "t" test at the 5% probability level.

RESULTS AND DISCUSSION

The number of days on the work schedule had a significant and quadratic effect on harvester (Figure 1A) and forwarder (Figure 1B) productivity. The harvester productivity values on the first, second, third and fourth day of the workday were 15.46; 15.45; 15.05; and 14.26 m³ h⁻¹, respectively. The forwarder productivity values were 65.17; 65.57; 64.77; and 62.79 m³ h⁻¹ on the first, second, third and fourth working days, respectively.

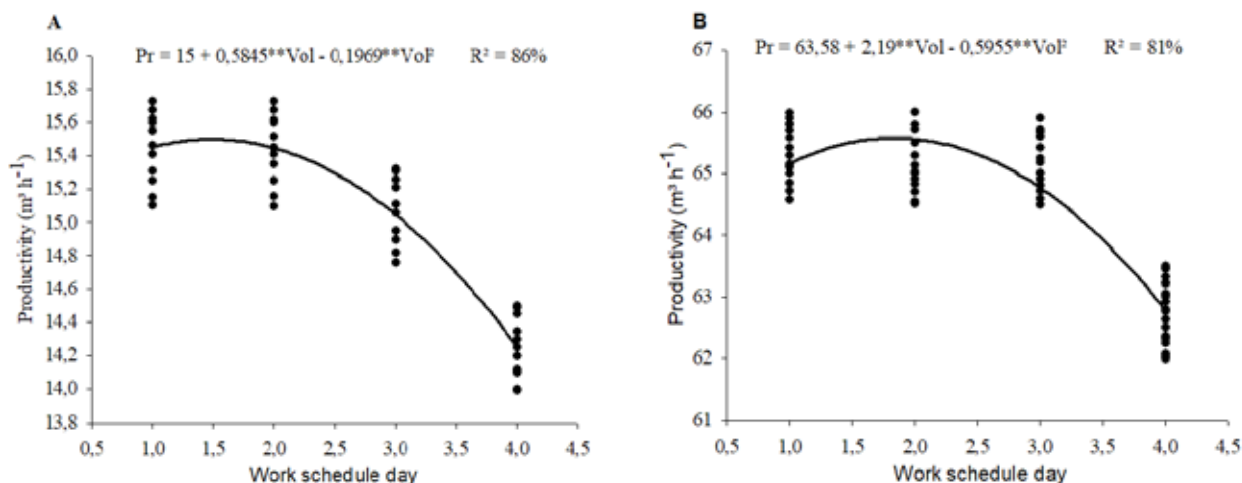


Figure 1. Adjusted models of productivity (Pr) as a function of the day of work for operators of the harvester (1A) and forwarder (1B) machines. Where: ** = significant at the 1% probability level; and R^2 = coefficient of determination

The harvester's productivity on the first and second day of the work schedule was similar. The productivity values of the third and fourth days of the work schedule, decreased by 2.62 and 7.74%, respectively, in relation to the average value of the first and second days. The productivity of the forwarder operators was similar in the first three days of the work schedule, with a more marked reduction in the fourth day. The value of the fourth day is 3.8% lower than the average productivity value of the first three days of the work schedule. The reduction in the operational performance of both machines is due to the occurrence of fatigue, with a predominance of symptoms of musculoskeletal diseases. In harvester operators, the symptoms started on the third day and became more intense on the fourth day of the workday. In the forwarder operators, fatigue symptoms were only observed on the fourth day of the workday. The low volume of the wood, 0.10 m³ tree, contributed to intensify the symptoms of fatigue in the harvester operators on the third day of the work schedule, due to the increase in repetitive movements. According to Santos *et al.* (2020b) the component most triggered by harvester operators is the left joystick, being triggered an average of 3,228 times per work shift. Repetitive wrist movements can cause various injuries, such as Carpal Tunnel Syndrome, Rotator Cuff Syndrome and Tendonitis (ØSTENSVIK *et al.*, 2008). According to Gerasimov and Sokolov (2014), forest machine operators are susceptible to injuries to the neck, arms and cervical spine, caused by excessive intensity at work, by staying

too long in ergonomically incorrect fixed positions and by repetitive short cycle movements.

The energy demand values had a significant and quadratic effect from the day of the harvester (Figure 2A) and forwarder (Figure 2B) operators' work schedule. The harvester's energy demand values were 1.33; 1.33; 1.39; and 1.51 L m⁻³ on the first, second, third and fourth day of the workday, respectively. Regarding the forwarder, the values were 0.230; 0.229; 0.231; and 0.238 L m⁻³ on the first, second, third and fourth working days, respectively.

The production cost had a significant and quadratic effect from the days of the work schedule of harvester (Figure 3A) and forwarder (Figure 3B) operators. On the first, second, third and fourth day of the work schedule, the production cost values for the harvester operators were 3.89; 3.89; 4.01; and 4.24 US\$ m⁻³, respectively. For the forwarder, the values were 0.83; 0.84; 0.83; and 0.86 US\$ m⁻³ on the first, second, third and fourth day of work, respectively.

The carbon dioxide values of the harvester and forwarder had a significant and quadratic effect from the days of the work schedule (Figure 4). On the first, second, third and fourth days, the CO_{2eq} values emitted by the harvester were 3.73; 3.73; 3.89; and 4.20 kg m⁻³, respectively. The forwarder, on the other hand, issued 0.641; 0.637; 0.644; and 0.662 kg m⁻³ on the first, second, third and fourth days of the work schedule, respectively.

The values of energy demand, production cost and carbon dioxide from the harvester reduced

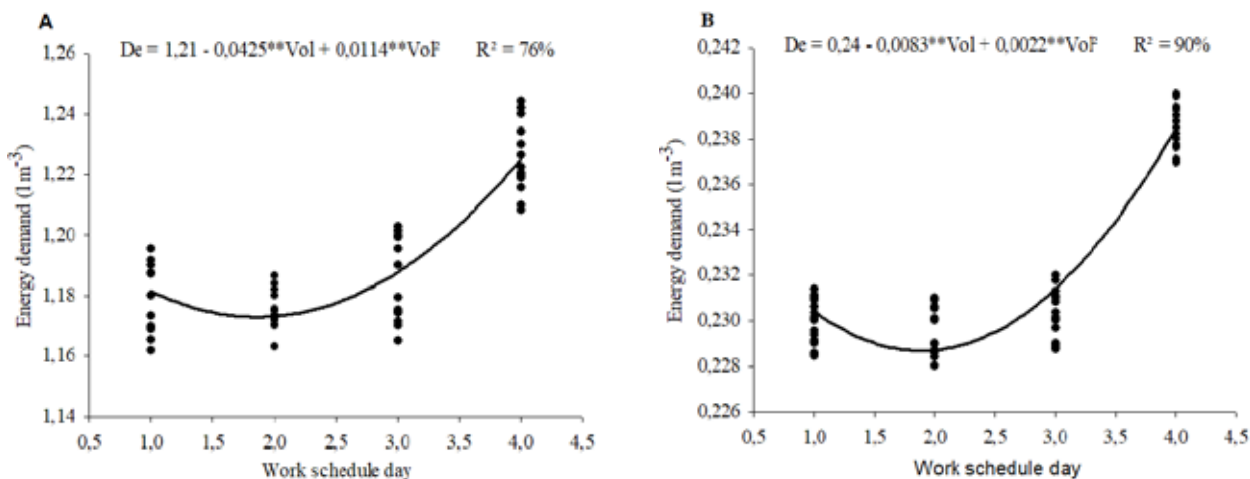


Figure 2. Adjusted models of energy demand (D_e) as a function of the day of work for operators of the harvester (2A) and forwarder (2B) machines. Where: ** = significant at the 1% probability level; and R^2 = coefficient of determination

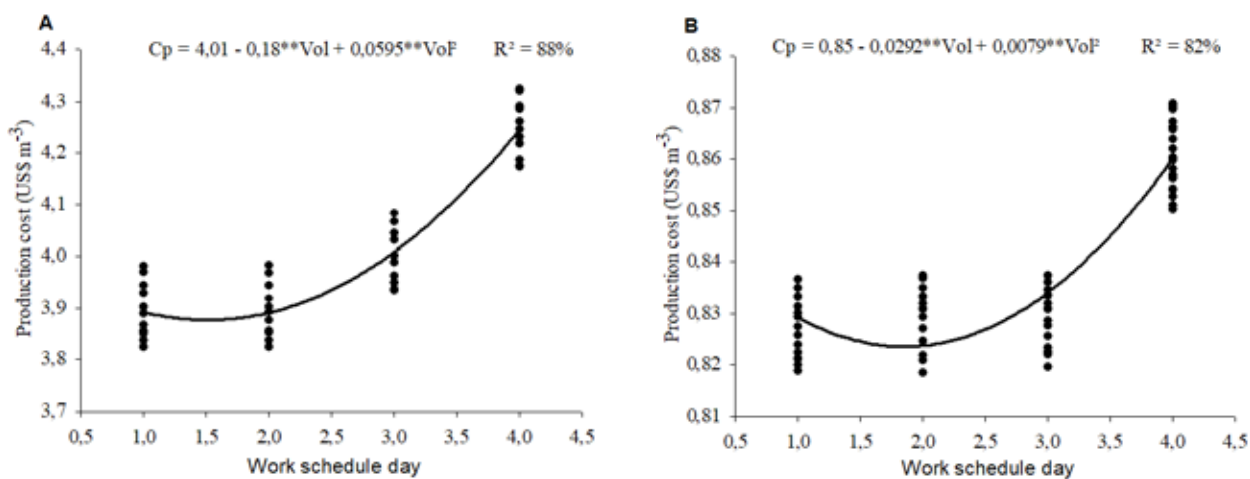


Figure 3. Adjusted model of production cost (C_p) as a function of the work schedule of harvester (3A) and forwarder (3B) operators. Where: ** = significant at the 1% probability level; and R^2 = coefficient of determination

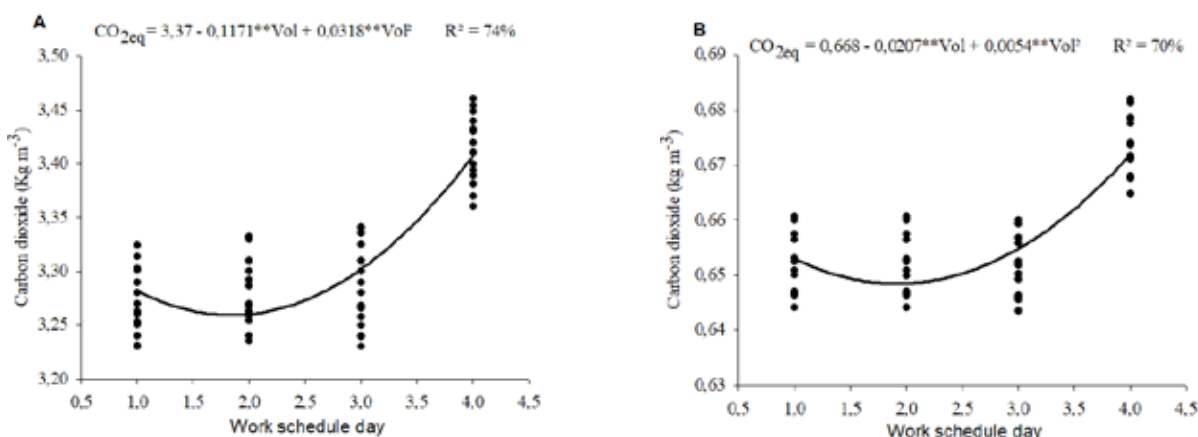


Figure 4. Adjusted models of carbon dioxide (CO_{2eq}) as a function of the day of work for operators of the harvester (4A) and forwarder (4B) machines. Where: ** = significant at the 1% probability level; and R^2 = coefficient of determination

more significantly on the third and fourth day of the work schedule. Regarding the forwarder, the reduction was only accentuated on the fourth day of the workday. On both machines, the decreases occurred due to the increase in hourly fuel consumption and reduced productivity. Such results corroborate those found by Santos *et al.* (2020a), who stated that the reduction in productivity and increase in fuel consumption of forest machines causes the reduction of energy efficiency and increases the cost of production and the emission of greenhouse gases. According to Zhang *et al.* (2016) productivity and energy demand are the most influential factors in the emission of polluting gases and in the cost of production.

If the forest harvesting operations were performed with a two-day work schedule, the values of energy demand, production cost and carbon dioxide for the harvester and forwarder subsystem would be 12; 8; and 11%, respectively. These

values would be lower than the values with the machines operating with a four-day work schedule. The operation with harvester and forwarder causes accumulative fatigue in operators, requiring a reduction in the work schedule.

The harvester operators began to mention symptoms of fatigue in the third (Table 1) and fourth (Table 2) day of the work schedule. In the forwarder operators, however, these feelings were found only on the fourth day of the work schedule (Table 3). The predominant symptoms in both operators were physical and mental tiredness with difficulties in visualization and concentration, impaired productivity and pain in the muscles of the neck, shoulder, arm, wrist and hands on the left and right side. According to Silva *et al.* (2014) forest machine operators experience pain and discomfort in the wrists / hands, back, lower or lower back, shoulders and neck, and taking rest, breaks and vacations alleviates musculoskeletal symptoms.

Table 1. Results of the bipolar questionnaire on the third day of the harvester operators work schedule

	1	2	3	4	5	6	7	
Rested					x			Tired out
Good concentration					x			Difficulty concentrating
Calm			x					Nervous
Normal productivity						x		Committed productivity
Visually rested						x		Visual tiredness
Absence of pain in the neck and shoulder muscles				x				Pain in the neck and shoulder muscle
Absence of back pain				x				Back pain
Absence of pain in the lower back			x					Pain in the lower back
Absence of pain in the thighs		x						Pain in thighs
Absence of leg pain		x						Pain in the legs
Absence of pain in the feet			x					Foot pain
Absence of headache		x						Headache
Absence of pain in the right arm, wrist or hand				x				Pain in the right arm, wrist, or hand
Absence of pain in the left arm, wrist or hand					x			Pain in the left arm, wrist or hand

Table 2. Results of the Bipolar questionnaire on the fourth day of the harvester operators work schedule

	1	2	3	4	5	6	7	
Rested						x		Tired out
Good concentration						x		Difficulty concentrating
Calm					x			Nervous
Normal productivity						x		Committed productivity
Visually rested						x		Visual tiredness
Absence of pain in the neck and shoulder muscles					x			Pain in the neck and shoulder muscle
Absence of back pain				x				Back pain
Absence of pain in the lower back		x						Pain in the lower back
Absence of pain in the thighs			x					Pain in thighs
Absence of leg pain		x						Pain in the legs
Absence of pain in the feet		x						Foot pain
Absence of headache	x							Headache
Absence of pain in the right arm, wrist or hand						x		Pain in the right arm, wrist, or hand
Absence of pain in the left arm, wrist or hand						x		Pain in the left arm, wrist or hand

Table 3. Results of the Bipolar questionnaire on the fourth day of the forwarder operators work schedule

	1	2	3	4	5	6	7
Rested						x	Tired out
Good concentration				x			Difficulty concentrating
Calm		x					Nervous
Normal productivity							x Committed productivity
Visually rested					x		Visual tiredness
Absence of pain in the neck and shoulder muscles						x	Pain in the neck and shoulder muscle
Absence of back pain					x		Back pain
Absence of pain in the lower back		x					Pain in the lower back
Absence of pain in the thighs			x				Pain in thighs
Absence of leg pain				x			Pain in the legs
Absence of pain in the feet					x		Foot pain
Absence of headache		x					Headache
Absence of pain in the right arm, wrist or hand						x	Pain in the right arm, wrist, or hand
Absence of pain in the left arm, wrist or hand					x		Pain in the left arm, wrist or hand

CONCLUSION

- The number of days in the work schedule of harvester and forwarder operators significantly influences the values of productivity, energy demand, production cost, carbon dioxide and the occurrence of fatigue in the operators. As a result, the reduction in the number of days on the work schedule makes forest harvesting operations more sustainable, from an economic, environmental and ergonomic point of view. Working schedule for two-day harvester operators and three-day forwarder is ideal for the operating conditions analyzed.

AUTHORSHIP CONTRIBUTION STATEMENT

SANTOS, D.W.F.N.: supervision and conception of the research, acquisition of data, analysis and interpretation of data, drafting and revising the work; FURADO JÚNIOR, M.R.F.: acquisition of data, analysis and interpretation of data, drafting and revising the work; DADALTO, J.P.: acquisition of data, analysis and interpretation of data, drafting and revising the work; NUNES, L.N.: acquisition of data, analysis and interpretation of data, drafting and revising the work; LEITE, D.M.: analysis and interpretation of data, drafting and revising the work.

DECLARATION OF INTERESTS

The authors declare that they have no known competing financial interests or personal

relationships that could have appeared to influence the work reported in this paper.

REFERENCES

BIETRESATO, M.; CALIGIURI, C.; RENZI, M.; MAZZETO, F. Use of diesel-biodiesel-bioethanol blends in farm tractors: first results obtained with a mixed experimental-numerical approach. **Energy Procedia**, v.158, n.5, p. 965-971, 2019.

COUTO, H. A. Índice TOR-TOM: 25 aplicações práticas na análise ergonômica, na avaliação de risco ergonômico, na prescrição de ações corretivas e no gerenciamento da produtividade segura. 2 ed. Belo horizonte: ERGO editora, 2012.

GERASIMOV, Y.; SOKOLOV, A. Ergonomic evaluation and comparison of wood harvesting systems in Northwest Russia. **Applied Ergonomics**, v.45, n.2, p. 318 -338, 2014.

MIYATA, E. S. Determining fixed and operating costs of logging equipment. St. Paul (MN): U.S. Dept. of Agriculture, Forest Service, North Central Forest Experiment Station. General Technical Report NC-55, 1980.

ØSTENSVIK, T.; VEIERSTED, K. B.; CUCHET, E.; NILSEN, P.; HANSE, J. J.; CARLZON, C.; WINKEL, J. A search for risk factors of upper extremity disorders among forest machine operators: A comparison between France and Norway. **International Journal of Industrial Ergonomics**, v. 38, p. 1017-1027, 2008.

PETRANOVIC, Z.; VUJANOVIC, M.; DUIC, N. Towards a more sustainable transport sector by numerically simulating fuel spray and pollutant formation in diesel engines. **Journal of Clean Production**, v. 88, p. 272-279, 2015.

SILVA, E. P.; MINETTE, L. J.; SOUZA, A. P.; MARÇAL, M. A.; SANCHES, A. L. P. Fatores organizacionais e psicossociais associados ao risco de LER/DORT em operadores de máquinas de colheita florestal. **Revista Árvore**, v.37, n.5, p.889-895, 2013.

SILVA, E. P.; MINETTE, L. J.; SANCHES, A. L. P.; SOUZA, A. P.; SILVA, F. L.; MAFRA, S. C. T. Prevalência de sintomas osteomusculares em operadores de máquina de colheita florestal. **Revista Árvore**, v.38, n.4, p.739-745, 2014.

SANTOS, D. W. F. N.; VALENTE, D. S. M.; FERNANDES, H. C.; SOUZA, A. P.; CECON, P. R. Technical, Economic, and Environmental Parameters of Excavator-Based Harvester in Function of Engine Speed and Hydraulic Pump Flow. **Croatian Journal of Forest Engineering**, v. 41, n. 2, p. 205-218, 2020a.

SANTOS, D. W. F. N.; VALENTE, D. S. M.; FERNANDES, H. C.; SOUZA, A. P.; MINETTE, L. J. Influence of pump pressure and engine speed on ergonomic parameters of forwarders operators. **Revista árvore**, v. 44, n. 1, p. e4425, 2020b.

ZHANG, F.; JOHNSON, D. M.; WANG, J.; YU, C. Cost, energy, use and GHG emissions for forest biomass harvesting operations. **Energy**, v. 114, p. 1053-1062, 2016.