Modelling Stand Damages and Comparison of Two Harvesting Methods

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Abstract – Nacrtak

This paper deals with the problem of tree damage in a remaining stand. Two models were used for assessment of stand damage over the entire production period. Damage accumulates on the trees and in the stand, which is why the total share of damage tends towards the limit 100% if the number of thinnings increases. Parameters used in the models were established partly by previous field measurements and partly by simulations measurements. Motor-manual and cut-to-length technologies were analysed and compared according to the total number of damaged trees and the structure of trees according to the number of injuries. It was found that motor-manual technology causes more damage to trees and results in worse tree structure, meaning more than one injury. Many unanswered questions provide plenty of opportunities for further research.

Keywords: stand damage, harvesting, technology, motor-manual, cut-to-length

1. Introduction – Uvod

Slovenian forestry has a long tradition of sustainable, multifunctional and co-natural forest management. The doctrine of forest management in Slovenia has been abundantly discussed and presented to the international community (Mlinšek 1977, Mlinšek 1994, Diaci and McConnell 1996). Uniform and group shelterwood systems are predominant. It is obvious that such doctrine demands a specific approach and exerts a considerable influence on all aspects of practical forestry (Matthews 1999). Forest harvesting has developed and it is adapted today to the specifics of silvicultural philosophy and to restrictions which originate from different sources. Clear-cuttings have been forbidden for many decades. Frequent thinnings (one to two cuttings in the same stand per decade – state forests), difficult terrain and large tree dimensions are the reason why motor-manual cutting and tractor or cable skidding are still predominant today. Final cuttings are more an exception than a rule.

Social changes in human resources, changes in energy prices, new possibilities in information technology and severe competition on the timber market are putting into question the economics and future of recent technologies, in which motor-manual cutting and skidding with various tractors prevail (M-M technology). The main reasons why cut-to-length (CTL technology) technology (harvester and forwarder) took off after 2000 were: demand for cost reduction and problems with recruitment of new professional workers for traditional forest work (Košir 2004). These reasons have been also crucial in the first debates in which forest enterprises tried to find a common language with the Slovenian Forestry Service. Compatibility of new CTL technology with the existing forest management doctrine raised a hot debate in which damage to existing trees and damage to forest soil were the most controversial issues. In this context damage to the remaining stand has been understood as injured trees with visible scars on stem, butt, roots or branches (scar area >10 cm²), broken branches in canopy and bent trees.

In case of tree damage (MM technology) we already have reliable data from abroad and from field observations (Krivec 1975, Ivanek 1976, Eriksson 1981, Butora and Schwager 1986, Leinss 1991, Košir 1998a, Sabo 1999 and other sources not mentioned here) as well as results gained from models (Košir and Cedilnik 1996, Košir 1996, Košir 2000). At the time when we published quite unfavourable results concerning tree damage research nobody took too much notice when traditional technologies were in question, while
a negative attitude towards the new CTL technology introduction appeared following the first cases of damage.

The performance of the general model of tree damage gave good results in the past, which were later confirmed by field observations. Therefore we decided to use the same model for comparing the damage to trees caused by traditional motor-manual and by the new CTL technology. We hope that in this manner we can present an unbiased assessment of this sensitive aspect of new technology introduction.

2. Research methods – Metode istraživanja

Tree damage models

Tree damage after forest operations decreases the value of forest yields in future, stability of stands, and it should be of utmost concern to every good forest owner (Spinelli 1999). Frequent thinnings also mean more chances for increased share of injured trees after finishing the work (Košir 2001). The model used in this comparison was developed for shelterwood forest management where cutting intensity was defined as the proportion between marked trees and all trees in the stand. The stand damage intensity was defined as the proportion between damaged trees after operations and all remaining trees.

We assumed that:

⇒ each tree has the same probability of being chosen for felling at a certain time,
⇒ each tree has the same probability of being damaged at the time of the last logging,
⇒ a tree which is damaged more than once in the same thinning is counted as one injury, and
⇒ a tree is marked as injured regardless of the severity of injury.

The share of damaged trees remaining in each thinning during the production period depends on the probability of the tree being chosen for cutting or probability of the tree having been damaged up to now. Obviously some trees will be damaged once, twice or more times at the end of the rotation period.

The basic model development and evaluation (Košir and Cedilnik 1996) gives more criteria than required for this analysis (such as increment of injuries). For our purposes we used the following formula, the so-called »rule of tree damage accumulation«:

\[ \Delta_n = 1 - (1 - \Delta_0) \prod_{i=1}^{n} (1 - \delta_i) \]  

where:

- \( \Delta_0 \) share of tree damage before forest operations started (beginning),
- \( \Delta_i \) share of tree damage in the stand after \( i \) thinning,
- \( \delta_i \) share of tree damage in \( i \) thinning,
- \( \Delta_n \) obviously tends to the limit = 1 if speaking of known \( \delta_i > 0 \) values.

The share of damaged trees is not directly dependant upon the intensity of thinning (equation 1), but as it has already been proved (Košir 2000), this dependence enters the model indirectly, because the intensity of cutting (\( \varepsilon_i \)) and skid trail density (\( G \)) impact the share of damaged trees (\( \delta_i \)) after thinning. Instead of intensity of cutting (\( \varepsilon_i \)), concentration of wood cut per ha can be used (\( V_i \)). We may write:

\[ \delta_i = f(V_i, G) \]

where:

- \( V_i \) intensity of cutting in \( i \) thinning (m³/ha),
- \( G \) density of skid trails (m/ha).

From the second model (where some results of field studies were used) the following formulas were used in this article:

\[ \delta_i = \frac{\delta_{vi} \cdot N_v + \delta_{si} \cdot (N_{si} - N_v)}{N_{si}} \]  

where:

- \( \delta_{vi} \) share of tree damage after \( i \) thinning along skid trails after \( i \) thinning,
- \( \delta_{si} \) share of tree damage after \( i \) thinning between skid trails after \( i \) thinning,
- \( N_v \) number of trees along skid trails,
- \( N_{si} \) number of trees in the whole stand after \( i \) thinning.

and:

\[ \delta_{vi} = 1 - e^{(V_i/G)} \]  
\[ \delta_{si} = a + b_1 \cdot V_i - b_2 \cdot G \]

where:

- \( e \) basis of natural logarithm,
- \( a, b_1, b_2 \) equation parameters.

For distinction between technologies the values from Table 1 were used.

Tree damage simulation

The above formulas give us a good estimation of total tree damage in the remaining stand after \( i \) thinnings, but we were also interested in the frequency of injuries to the trees at the end of the rotation period. The question was: how many injuries can we expect to the trees and how many removals?
After i thinnings we can expect a certain number of trees to have injuries, but this number will be small, as we must expect that during the thinning period the majority of injured trees have been already removed. To answer the question above we built a simulation matrix with \( N_s = N_0 \) rows and \( i = n \) columns. Trees were randomly chosen for cut and marked as injured in the range of \( V_i \) and \( d_i \) for each technology separately. The final share of tree damage was the same as the share calculated using the basic model.

Apart from numeric values of the simulated events we can also make a graphical picture of the situation after each thinning. The main advantage of the simulation is that we can analyse the frequency of injury distribution after each thinning. This provides the possibility to calculate the value of money lost due to decay. The graphical part of the simulation is also valuable for student training.

3. Results of research– Rezultati istraživanja

Results of the general model

The results are partly shown in Table 2 (formulas 2, 3 and 4). The reason for this calculation was to get the whole picture of expected differences between the two technologies. First we calculated \( \delta_i \) as an input variable for formula 1 and for the simulation program.

After i thinnings we can expect a certain number of trees to have \( \delta_i \) injuries, but this number will be small, as we must expect that during the thinning period the majority of injured trees have been already removed. To answer the question above we built a simulation matrix with \( N_s = N_0 \) rows and \( i = n \) columns. Trees were randomly chosen for cut and marked as injured in the range of \( V_i \) and \( d_i \) for each technology separately. The final share of tree damage was the same as the share calculated using the basic model.

Computed \( \delta_i \) do not differ significantly from field studies. For MM technology \( \delta_i \) are comparable with the averages for this combination of skid trail density and thinning density from the field measurement (Košir 2000). Another example (Košir and Robek 2000) shows that in an artificially established Scotch pine stand, about 50 years old, 8% of injuries were found in one cutting-unit and 12% of injuries in the second cutting-unit after the application of CTL technology (harvester Timberjack 1270 and forwarder Timberjack 1410).

Fig. 1 shows the results of calculations of \( D_i \) for MM and CTL technologies (formula 1). Early thinnings in the model start at the age of 30 years and continue up to 160 years when the rotation period ends and regeneration cuttings begin. The total number of damaged trees in the stand continuously grows and reaches around 90% at the end of the rotation period.
This is a rather shocking result, and the question is whether it is possible to prove such predictions by a field observation. The answer is positive if we take into account the fact that many smaller injuries disappear during the decades of tree growth. In practice it is thus possible to expect some smaller values of damaged trees (Robek and Medved 1997) than shown in Table 3, where the results of the field measurement are shown (Kožir 1998a). In old stands 64–70% of damage have been recorded. The difference between model predictions and the actual situation can be explained with some facts that are not included in the model, but have an impact on field observations, such as the disappearing of visible injuries due to the healing of stem scars and the disappearing of wounded branches over a long period of time, insufficient knowledge of past technologies and the rate of damages they had induced, as well as insufficient accurate evidence about past cuttings.

It can also be concluded from Figure 1 that the difference between MM and CTL technology is not constant during the whole tree age, but that it reaches its maximum value (0.10) at the age of 70–80 years and from then on decreases toward the limit = 0.
Motor-manual felling and extraction with tractors show very bad results in early thinnings in comparison with CTL technology.

**Results of simulations**

An overall picture of tree damage behaviour during the rotation period should be close to the general model, though we can expect some minor deviations due to the stochastic process. The advantage of this approach is that we can obtain the structure of injuries according to the time of appearance and the number of trees, which have been injured several times (Table 4). We may also analyse the injuries of the removed part of the stand. These results enable

<table>
<thead>
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<th>Table 4 Number of trees in stands in 30-year age classes</th>
<th>Broj stabala u sastojini za 30-godišnje dobne razrede</th>
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<tr>
<td><strong>MM</strong></td>
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<td>Year</td>
<td>Undamaged trees</td>
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<td>Neostičena stabla</td>
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<td><strong>CTL</strong></td>
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**Fig. 2** Differences in number of injured trees between MM and CTL technology

**Slika 2.** Razlike u broju oštećenih stabala između sustava MM i CTL za pridobivanje drva
us to make a better assessment of the lost value than ever made so far (Košir 1998b). Nevertheless, this is not within the scope of this article.

Differences in the number of injured trees after the whole rotation period are shown in Fig. 2. With CTL technology we can expect a greater number of undamaged trees. Later in the stand development we can also expect a greater number of trees that have been injured once or twice on one hand, and a smaller number of trees that have been damaged more times on the other hand, than is the case when using MM technology.

The whole structure of relative frequencies according to age is given in Fig. 3 and 4. First we notice
similar flows of undamaged stand curves, which are slowly closing towards the limit of 100% damaged trees. The share of tree injured once appears after the first thinning and at 70 (MM) and 90 (CTL) years it reaches its maximum, and thereafter slowly decreases as more and more trees with one injury receive more injuries or are removed from the stand. Trees with two injuries appear one thinning later and show a similar trend. The maximum is at 100 (MM) or 150 (CTL) years, and later the share of such trees slowly decreases. Other curves in both figures show similar logic flow. Comparison of both figures shows that the CTL curves have maximums at later stages of the stand, because there is less damage at each thinning.

This can be better understood if we consider Figure 2 once more, where the situation after the end of the observed period is shown. The MM system shows a strong tendency of injury distribution towards more injuries per tree. This also means that the maximum of distribution is at three instead of two injuries per tree, as shown in the distribution of CTL technology. A compared distribution of injuries in earlier development stages shows the same relations between MM and CTL technologies, but with a higher number of undamaged trees (0 injuries) and a smaller number of trees injured more than once.

4. Discussion and conclusions – Rasprava i zaključki

Models of tree damage in the remaining stand are a valuable tool for analysing the consequences of forest operations in the time to come. It is of minor importance that the technologies are changing in the direction of less brute force, and what is even more important, machine operators, supervisors and forest owners are more aware than before of the damaging potential of modern technology. Education and training of machine operators and all others who deal with forest management is therefore a permanent issue. With respect to the described facts, the change of technology means that the same relations will appear on a different level, hopefully better for the forest. In this paper we compared two technologies which seem to compete at present in different conditions, where stand composition and terrain characteristics play a major role. An older technology, where motor-manual work prevails, has been studied much closer and for a longer period of time. Cut-to-length technology is well known, with a long tradition in the Nordic and many other countries, but the results of damage studies (Frödig 1992, Frohm 1993) or models (Siren 1999, Dvořák 2005) cannot be used directly in Slovenian conditions, as stand composition, stand density, terrain characteristics and other circumstances of forest operations are different. This does not mean that the validation of the model is questionable, but there is a doubt whether the input variables are reliable and representative for a certain technology. There is also a challenging question of whether historical data can support our findings.

This paper showed that under the given assumptions CTL technology causes less damage to the forest. In the long run that means a slower increase of damaged trees in the stand and better distribution of accumulated damages in the stand. This would improve the stability of stands (less damage by bark beetles, for example) and increase the yield value. Other advantages and disadvantages of CTL technology have not been discussed in the paper.

There are still numerous questions connected to CTL technology and stand damages. Stand density influences considerably the share of injuries in the stand. If the reports of tree damage from northern countries (<0.05) are compared with those from Central Europe, a large discrepancy is obvious. Stand density is already included into the model, but not directly. In this respect the model should be upgraded by additional choices, based on actual field measurements.

During recent observations and measurements (not yet published), according to the slightly modified Frödig method (1992), we noticed that tree damages are greater when the machine operator is working in a dark environment (with lights engaged). There is also no reliable research of extended work time (Nicholls et al. 2004) and work quality where work quality also includes tree damage. Answers to these and other questions will also improve the results of comparisons described above.

5. References – Literatura


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Sažetak

Modeliranje oštećenja sastojine i usporedba dvaju sustava za pridobivanje drva

Gospodarenje se šumama u Sloveniji zasniva na prirodnoj održivosti i multifunkcionalnosti. Prevlada grupično gospodarenje raznodobnim sastojinama, a čiste su sjeće već desetljećima zabranjene. Zbog čestih

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oprhodnje postavljeno pitanje: koliko se ozljeda može očekivati na stablima i deblima? Za odgovor na to pitanje stabala u sastojini nakon i-toga prorjeđivanja te je zbilje da se sazna učestalost ozljeda na stablima na kraju dijelom zbog same sječi tih stabala. Udio dva puta oteženih stabala najveći je za ručno-strojni sustav za godinu za sustav CTL za pridobivanje drva, nakon čega udio opada dijelom zbog povećanja broja ozljeda na stablu, a dijelom zbog same sječe tih stabala. Uspoređena su oba sustava s obzirom na ukupan broj oteženih stabala, ali i struktura oteženih stabala ovisno o ponavljanju oteženja svakoga stabla pri izvođenju žušnih radova u različitim razdobljima (prorede).

Postavljene pretpostavke su:

\[ \Rightarrow \] jednaka je vjerojatnost da svako stablo bude posječeno u određenom vremenu

\[ \Rightarrow \] jednaka je vjerojatnost da svako stablo bude oteženo za vrijeme posljednje sječe

\[ \Rightarrow \] svako stabilno koje je oteženo više od jedanput u istom sijeku broji se kao jedno oteženje

\[ \Rightarrow \] stablo je označeno kao oteženo bez obzira na težinu ozljede.

Osnovni model razvoja i procjene primijenjuje više kriterija nego što je bilo potrebno za ovu analizu, stoga je primijenjeno tzv. »pravilo akumulacije oteženih stabala«. Udio oteženih stabala nije neposredno ovisan o intenzitetu prorjeđivanja, međutim ta se ovisnost posredno javlja kroz intenzitet sječe (v), gustoću vlaka (G) i udio oteženih stabala (z) nakon i-te prorede. Primijenjene su jednadžbe omogućile dobru procjenu ukupne oteženosti stabala u sastojini nakon i-toga prorjeđivanja te je zbog želje da se sazna učestalost ozljeda na stablima na kraju ophodnje postavljeno pitanje: koliko se ozljeda može očekivati na stablima? Za odgovor na to pitanje napravljena je simulacijska matrica sa \( N_s = N_0 \) reduva i \( 1 = n \) stupaca. Uspoređeni uzorki oteženih stabala bio je jednak kao i kod upotrebe osnovnog modela.

Slika 1 prikazuje usporedbu udjela oteženih stabala nakon i-te prorede za dva načina pridobivanja drva tijekom cijelege ophodnje. Ukupni udio oteženih stabala stalno raste do vrijednosti 90 % na kraju ophodnje. Iako su to zapanjujući rezultati, postavljaju se pitanja da li su navedeni rezultati umjetni ili fizički primjereni. Uspoređen je i oteženje stabala tijekom cijelege ophodnje za vrijeme posljednje sječi (v), estimacija oteženosti stabala (z) i količina sječa (v). Osnovni model razvoja i procjene primijenjeni su na ukupan broj oteženih stabala, ali i struktura oteženih stabala ovisno o sječi.

U tablici 4 prikazani su rezultati simulacije. Prednost je ove metode procjene u tom što se mogu dobiti podaci o oteženosti ovisno o frekvenciji ozljeda za vrijeme posljednje sječi (v). Uspoređeni uzorki oteženih stabala bio je jednak kao i kod upotrebe osnovnog modela. U spremištu se jednaka je vjerojatnost da svako stablo bude postavljanje na stabilni stav: za oteženje stabala na stablu (na ukrupnu reduv) (S) i za vrijeme posljednje sječi (v) i količina sječa (v). Osnovni model razvoja i procjene primijenjeni su na ukupan broj oteženih stabala, ali i struktura oteženih stabala ovisno o sječi.

pridobivanje drva u 100-oj godini, a za sustav CTL u 150-oj godini starosti. Ostale krivulje pokazuju sličan tijek. Usporedbom tih krivulja jasno je da sustav CTL za pridobivanje drva doseže vrhunac u kasnijim godinama ophodnje jer je manje oštećenja za vrijeme svakoga prorjeđivanja.

Istraživanje je pokazalo da sustav CTL za pridobivanje drva uzrokuje manje oštećenja u šumi, sporije povećanje broja oštećenih stabala tijekom vremena, ali i bolju distribuciju nakupljenih oštećenja u sastojini, što povećava stabilnost sastojine, ali i povećava vrijednost drva.

Broj stabala po jedinici površine utječe na udio ozljeda pri primjeni sustava CTL te ako se usporede podatci o oštećenjima stabala iz skandinavskih zemalja (<0,05) s podacima iz srednje Europe, dolazi do određenih odstupanja pa je stoga potrebno unaprijedjeno postojećega modela pomoću stvarnih terenskih mjerenja.

Tijekom nedavnih istraživanja i mjerenja (koja još nisu objavljena) primjenom modificirane Frödigove metode (1992) primijećeno je da su oštećenja na stablima veća ako operater radi u tamnom okruženju (s upaljenim svjetlima). Također ne postoje pouzdana istraživanja o produljenom radnom vremenu i samoj kakvoci rada koja uključuje i količinu nastalih oštećenja na stablima. Odgovori na ta i druga pitanja pojasnit će ovdje dobivene rezultate.

Ključne riječi: oštećenja sastojine, sječa, tehnologije, ručno-strojna sječa, strojna sječa

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