Forest Road Access Decisions for Woods Chip Trailers Using Ant Colony Optimization and Breakeven Analysis

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Abstract – Nacrtak

Non-conventional products provide opportunities for the forest industry to increase economic value from forests; however, these products may require transport by specialized vehicles. The existing forest transportation network was not necessarily designed to the road standards required for these specialized vehicles. Several road modifications can be made to give specialized vehicles access to the forest transportation network including filling the ditch, removing the superelevation, reversing the superelevation, or reconstructing the roadway. For each investment, there is an associated vehicle that can traverse the road segment if the investment is made. For scheduling multiple biomass operations over a road network, we use the Ant Colony heuristic to identify the combination of optimal vehicle choices and road modifications to effectively transport non-conventional products. These combinations related to a 27% reduction in total transportation costs. For isolated biomass operations, we use breakeven analysis to make the vehicle selection and road modification option. Decisions for isolated biomass operations depend on road modification cost, transport volume, and transport costs on forest and highway roads.

Keywords: ant colony optimization, biomass transport, vehicle accessibility

1. Introduction – *Uvod*

The production of high valued non-conventional products, such as utility poles or the production of low valued products such as chips or hogfuel, provide opportunities for the forest industry to increase economic value from forests. However, most of the forest transportation system has been designed and built for long-log, stinger-steered trailers (Sessions et al. 2010) and there is little engineering record of road design or location throughout the forest industry (Craven et al. 2011).

This lack of engineering records provides a challenging environment in the assessment of transporting non-conventional products. The primary challenge to hauling non-conventional products, on specialized vehicles, is determining if the vehicle can navigate the horizontal and vertical geometry unloaded and loaded, as well as turning around near the landing. These specialized vehicles include truck tractors pulling pole trailers with rear self-steering axles, pole trailers with stinger-steered axles, fifth-wheel chip trailers (with and without self-steering rear axles), and stinger-steered chip trailers. We define a pole trailer as a stinger-steered trailer with a bunk-to-bunk distance longer than 8.5 m, hauling logs that are longer than 13.7 m. We focus on the economical assessment of varying sized chip trailers (chip vans) throughout the forest transportation network for the remainder of the paper, although the principles are the same for other specialized trailers.

2. Problem Description – *Problematika*

Several choices can affect the accessibility of these specialized vehicles. These choices include temporarily filling the ditch, removing or reversing the superelevation to reduce lateral tire slip, and widening the roadway. During the dry months, temporarily filling the ditches or changing the superelevation of the roadway are options that permit specialized vehicles access. Temporarily filling the ditch provides a greater road width for the specialized vehicle to pass, usually 0.5 to 1.5 m of extra road width. Single lane forest roads surfaces are insloped, outsloped, or crowned. Positive superelevation of the road surface is often constructed into forest roads to counteract centrifugal force created by vehicles in curves (Oglesby and Hicks 1982). Negative superelevation of the road surface is sometimes constructed into curves to adjust the normal forces on the driving axles to permit climbing steeper grades (Anderson and Sessions 1991). Outsloping a forest road is sometimes used to drain water from the road surface without diverting water to ditches and insloping of forest roads is done for safety when roads are icy (Bowers 2006). During the dry months, superelevation may not be needed either because side friction is greater and/or cross slope drainage is not an issue; providing an opportunity to alter the road surface to reduce lateral tire slip toward the inside of a curve. Two options exist when altering the superelevation (1) remove the superelevation and (2) reverse the superelevation. Removing the superelevation reduces the amount of off-tracking that a vehicle produces by reducing the amount of lateral tire slip due to gravity (Glauz and Harwood 1991). Reversing the superelevation could be used to counteract off-tracking; allowing the weight of the vehicle and the effects of gravity on an inclined plane to counter the effects of off-tracking. Lastly, forest engineers and managers can affect the outcome by redesigning the roadway to allow these vehicles access along the entire roadway length. This is achieved by widening the roadway and removing obstacles close to the roadway such as standing trees.

Fig. 1 A 13.7 m drop center 5th wheel chip van being loaded on a forest road in Lane County, Oregon

Slika 1. *Poluprikolica za šumsku sječku dugačka 13,7 m (utovar na sredini prikolice) tijekom utovara na šumskoj cesti u Lane County, Oregon*

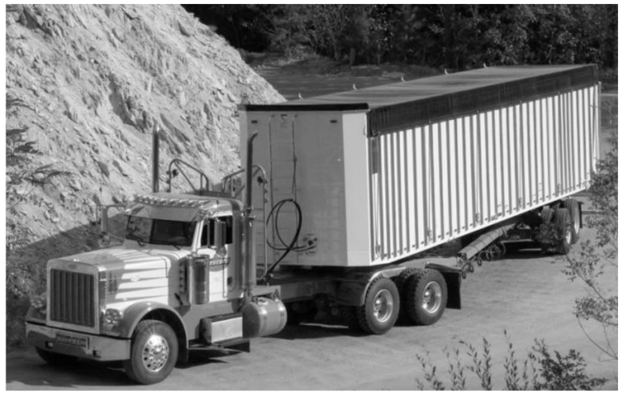

Fig. 2 A stinger-steered chip van. Photo courtesy of Western Trailer Company

Slika 2. *Samokretna prikolica za šumsku sječku. Slika dobivena od Western Trailer Company*

Each modification option has an associated cost and benefit. For example, if a 13.7 m drop center 5th wheel chip van (Fig. 1) needs an extra half meter of road width to access a harvest unit, the ditches might be temporarily filled to allow the 5th wheel chip van access. If the ditches were not filled, the only vehicle that might have access to the unit would be a stinger-steered chip trailer (Fig. 2). Not only does the amount of off-tracking vary between vehicles, so does the volume of chips or hogfuel consistent with weight restrictions that these vehicles can haul. The operating cost and traveling speed vary for each vehicle configuration, creating a multi-dimensional problem.

We look at two cases. The first case involves scheduling multiple biomass operations over a road network, where trucks from several biomass operations can take advantage of the same road investment. The second case looks at isolated biomass operations, where the road investment is used by only one operation. For both cases, mixed integer linear programming can be used to exactly solve the underlying mathematical problem. However, for the second case it is more convenient to use a breakeven analysis. For larger problems of the first case, due to the solution time for mixed integer programming, heuristics such as Ant Colony Optimization (ACO) can be used to determine a high quality solution for vehicle type, path, and road modifications for transporting biomass. Other useful heuristics are described by Glover and Kochenberger (2002), Hoos and Stutzle (2005) and Geem (2009).

3. Mathematical Formulation – Case One *Matematički prikaz – slučaj prvi*

The mathematical problem is to minimize the sum of road modifications and biomass transportation costs. Let $G = (N, A)$ be a directed network with nodes N and arcs (i,j) within A. We associate with each node i within N a number $S(i)$, which indicates the supply or demand depending on whether $S(i) > 0$ or $S(i) < 0$. The minimal cost problem is then:

Minimize

$$\sum_{(i,j)\in A} FC_{ij}^{t} \times Y_{ij}^{t} + \sum_{(i,j)\in A} \sum_{t\in T} VC_{ij}^{t} \times Volume_{ij}^{t}$$

$$\forall (i,j) \in A,\ t \in T \qquad (1)$$

Conservation of Flow

$$\sum_{\{ji(i,j)\in A\}} Volume_{ij}^{t} - \sum_{\{ji(j,i)\in A\}} Volume_{ji}^{t} = V^{t}(i) \quad \forall\ i \in N \qquad (2)$$

Sale Volumes

$$\sum_{t\in T} V^{t}(i) = S(i) \qquad \forall\ i \in N \qquad (3)$$

Road Triggers

$$\sum_{t\in T} M \times Y_{ij}^{t} \geq Volume_{ij}^{1} \qquad \forall (i,j) \in A \qquad (4)$$

$$\sum_{t\in T(t\geq 2)} M \times Y_{ij}^{t} \geq Volume_{ij}^{2} \qquad \forall (i,j) \in A \qquad (5)$$

$$\sum_{t\in T(t=3)} M \times Y_{ij}^{t} \geq Volume_{ij}^{3} \qquad \forall (i,j) \in A \qquad (6)$$

Decision Variables

$$Y_{ij}^{t} = \{0,1\} \qquad \forall (i,j) \in A, t \in T \qquad (7)$$

$$Volume_{ij}^{t} \geq 0 \qquad \forall (i,j) \in A,\ t \in T \qquad (8)$$

Equation (1) is the objective function. FC_{ij}^{t} is the fixed cost to modify link *ij* to allow truck type *t* access. Y_{ij}^{t} is a binary variable, zero if the link is not used, and one if the link is used. VC_{ij}^{t} is the round trip variable cost over link *ij* in truck type *t*, (\$/tonne). $Volume_{ij}^{t}$ is the amount of volume crossing link *ij* in truck type *t*, (tonnes). Equation (2) provides conservation of flow at each node for each truck type. $V^{t}(i)$ is the volume entering each node *i* for each truck type *t*, (tonnes). Equation (3) requires that the total supply or demand at each node $S(i)$ (tonnes), equal the sum of the volume transported over all truck types. Equation (4) requires that the road modification for truck type 1 (the lowest standard truck type) be made to at least pass truck type 1, if there is volume passing over link *ij* in truck type 1. Equation (5) requires that the road modification for truck type 2 (the moderate standard truck type) be made to at least pass truck type 2, if there is volume passing over link *ij* in truck type 2. Equation (6) requires that the road modification for truck type 3 (the highest standard truck type) be made to pass truck type 3, if there is volume passing over link *ij* in truck type 3. Equation (7) requires that the road trigger for link *ij* for truck type *t* be a binary variable, zero or one. Equation (8) requires that the volume passing over link *ij* for truck type *t* be equal to or greater than zero.

4. Review of Ant Colony Optimization *Opis optimizacije metodom mravlje kolonije*

The ACO (Dorigo and Stutzle 2004) is based on the analogy of ants searching for food. Ants randomly walk in search of food leaving a pheromone behind as they travel. The pheromone is a scent that influences other ants to take that path. As more ants travel over the same path the pheromone increases, increasing the possibility of an ant choosing that path. This process continues until all ants are following the same path to the food source. The ACO heuristic has been used to solve fixed cost and variable cost forest transportation problems with side constraints (Contreras et al. 2008). Outside of the forest industry, this heuristic has been used to solve vehicle route scheduling problems, capacitated vehicle routing problems, and other scheduling problems (Donati et al. 2008, Rizzoli et al. 2007).

5. Ant Colony Optimization – *Optimizacija metodom mravlje kolonije*

The ACO developed in this paper is designed to minimize the total transportation cost. The total transportation cost is the sum of the modifications costs plus the round trip variable costs multiplied by the volume of each harvest unit. If a truck is loaded at sale *x*, it must make it to destination *z* using the same truck. If different types of trucks use the same link, the one with the maximum fixed cost will be applied. Therefore, if road modifications are applied so that a 16.2 m drop center 5th wheel chip van (Fig. 3) can navigate the road, no other modifications need to take

Fig. 3 A 16.2 m drop center 5th wheel chip van near Port Angeles, Washington

Slika 3. *Poluprikolica za šumsku sječku dugačaka 16,2 m s utovarom na sredini u blizini Port Angeles, Washington*

place for other truck types. The ACO regards each road modification option as a separate link. In other words, between each node, three links exist; one that has no fixed cost, one that has a moderate fixed cost, and one that has a large fixed cost; all of which end up at the same node (Fig. 4). As the algorithm progresses through each set of ants, each ant in each set has a designated modification option that it will choose from as it progresses through the network. It was chosen to have three kinds of ants; a truck type 1 ant, a truck type 2 ant, and a truck type 3 ant to diversify the search. With this formulation, each modification option has its own set of pheromones. The starting pheromones provided an equal probability choosing each link leaving a node for each truck type. As the algorithm identifies a lower total cost route from each sale, the links that are not part of that path have their pheromones decay. We used a constant decay factor of 25 %.

The ACO was compared to a mixed integer linear programming model, using a small network (Fig. 4). The large black circles are the nodes in the network. The small black circles are the road modification option for the 16.2 m drop center 5th wheel chip van, the small horizontally hatched circles are the road modification option for the 13.7 m drop center 5th wheel chip van, and the small white circles are the no road modification option for the stinger-steered chip van. In this formulation, three different degrees of road modification could be applied, no modification, moderate modification, or major modification. The no modification option will only allow a stinger-steered chip van access. The moderate modification option will allow a stinger-steered chip van and a 13.7 m drop center 5th wheel chip van access. The major modification will allow all three trucks access to the road segment. Each truck has a different hourly operating cost. The stinger-steered chip van has an estimated hourly cost of $ 95.37, the 13.7 m drop center 5th wheel chip van hourly cost is $ 90.95, and the 16.2 m drop center 5th wheel chip van hourly cost is $ 99.79 (Table 1). We assumed cost per hour is the weighted average hourly cost and did not vary with speed or road type.

The modification costs vary by the magnitude of the required modifications. The moderate modification option was assumed to require removing the superelevation within the roadway and filling the ditches to allow the 13.7 m drop center 5th wheel chip van access. We assumed that these modifications would cost $ 3,281 per km. The major modification option

Table 1 Chip Van Operating Characteristics for the three truck types

Tablica 1. *Tehničke značajke triju promatranih tipova prikolica*

Trailers *Prikolice*	Volume Capacity, m^3 *Obujam,* m^3	Speed on Forest Roads (empty or loaded), km/h *Maksimalna brzina na šumskoj cesti (puna ili prazna),* km/h	Speed on Highways (empty or loaded), km/h *Maksimalna brzina na autocesti (puna ili prazna),* km/h	Operating Cost, $/h *Jedinični trošak,* $/h	Modification Cost, $/km *Troškovi rekonstrukcije,* $/km
12.8 m Stinger Steered *Samokretna prikolica dugačka 12,8 m*	73.6	16.1	72.4	$ 95.37	$ 0
13.7 m Drop Center 5th wheel *Poluprikolica dugačka 13,7 m s utovarom na sredini*	93.4	16.1	72.4	$ 90.95	$ 3,281
16.2 m Drop Center 5th wheel *Poluprikolica dugačka 16,2 m s utovarom na sredini*	113.3	16.1	72.4	$ 99.79	$ 9,843

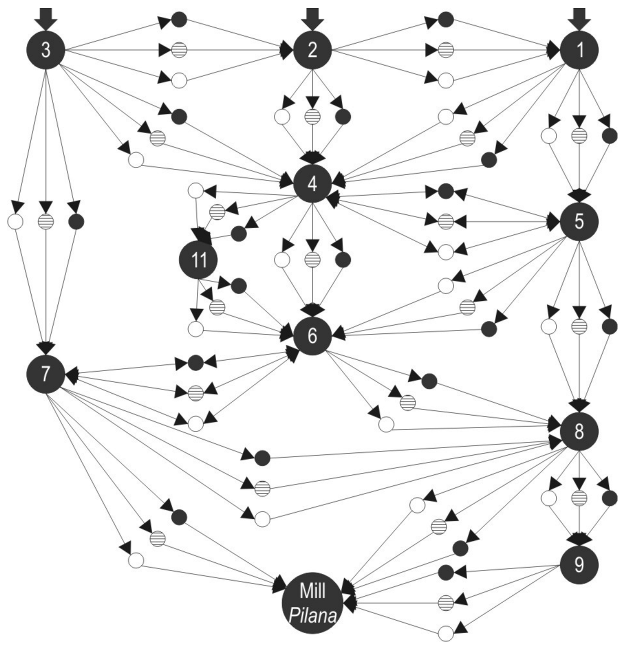

Fig. 4 Small example road modification network, adapted from (Sessions 1985)

Slika 4. *Primjer modificirane mreže šumskih prometnica (prilagođeno iz Sessions 1985)*

was assumed to require filling the ditches, reversing the superelevation, and widening the roadway on a few select curves. These modifications were estimated to cost $ 9,843 per km (Table 1). We assumed that only half of the link length needed to be modified because forest road curves are approximately half of the transportation network.

Table 2 Sale Nodes

Tablica 2. *Mjesta prodaje*

Volume of Biomass – *Volumen biomase*		
Harvest Node *Mjesto iveranja*	Destination Node *Mjesta isporuke*	Biomass, m^3 *Biomasa,* m^3
1	10	135,921
2	10	28,883
3	10	175,564

The sale nodes for the small network (Fig. 4) are nodes 1, 2, and 3. The associated amount of biomass for each sale (chips or hogfuel) is identified in Table 2. All of the biomass is to be delivered to only one mill (Node 10). The haul and modification costs per link are provided in the appendix (Table 5).

The ACO had a stopping criterion of 1,000 iterations. The heuristic converged on its solution rather quickly (iteration 282). The optimal solution to this problem using the ACO is $ 72,140. This amounted to $ 6,225 in modification costs and $ 65,915 in hauling costs. The optimal path is shown for each sale in Table 3 and Fig. 4. There were 1,454 trips from Unit 1 to the

Table 3 The Optimal Path for the Small Network Using Ant Colony Heuristic

Tablica 3. *Optimalni pravac izvoženja prema metodi mravlje kolonije*

Total Cost – *Ukupni troškovi prijevoza*	$ 72,139.50	–
Sale 1 – *Prodaja 1*	Sale 2 – *Prodaja 2*	Sale 3 – *Prodaja 3*
Truck Type – *Vrsta prikolice*	Truck Type – *Vrsta prikolice*	Truck Type – *Vrsta prikolice*
13.7 m Drop Center 5th wheel *Poluprikolica dugačka 13,7 m s utovarom na sredini*	13.7 m Drop Center 5th wheel *Poluprikolica dugačka 13,7 m s utovarom na sredini*	16.2 m Drop Center 5th wheel *Poluprikolica dugačka 16,2 m s utovarom na sredini*
Best Node Path – *Optimalni pravac izvoženja*	Best Node Path – *Optimalni pravac izvoženja*	Best Node Path – *Optimalni pravac izvoženja*
1	2	3
5	4	7
6	11	10
7	6	–
10	7	–
–	10	–

Table 4 The Optimal Path for the Small Network Using Mixed Integer Programming
Tablica 4. *Optimalni pravac izvoženja prema metodi mješovitoga cjelobrojnoga linearnoga programiranja*

Total Cost – *Ukupni troškovi prijevoza*	$ 72,154.26	
Sale 1 – *Prodaja 1*	Sale 2 – *Prodaja 2*	Sale 3 – *Prodaja 3*
Truck Type – *Vrsta prikolice*	Truck Type – *Vrsta prikolice*	Truck Type – *Vrsta prikolice*
13.7 m Drop Center 5th wheel *Poluprikolica dugačka 13,7 m s utovarom na sredini*	13.7 m Drop Center 5th wheel *Poluprikolica dugačka 13,7 m s utovarom na sredini*	16.2 m Drop Center 5th wheel *Poluprikolica dugačka 16,2 m s utovarom na sredini*
Best Node Path – *Optimalni pravac izvoženja*	Best Node Path – *Optimalni pravac izvoženja*	Best Node Path – *Optimalni pravac izvoženja*
1	2	3
5	4	7
6	11	10
7	6	–
10	7	–
–	10	–

Mill, 309 trips from Unit 2 to the Mill, and 1,550 trips from Unit 3 to the Mill.

The ACO solution was compared to a mixed integer solution (Table 4, Fig. 5). The mixed integer and ACO produced similar results; a $ 13 difference between the two approaches. This was the result of rounding when formulating the mixed integer problem. Both methods used the same truck types and paths to transport the biomass to the mill. This small example illustrates that the heuristic appears reasonable for determining near optimal solutions for similar road modification problems.

6. Application to a realistic forest transportation network – *Primjena na stvarnoj šumskoj transportnoj mreži*

Following the favorable results of the small network, the ACO heuristic was used on the McDonald Forest, to determine the least cost path for future harvesting activities. McDonald Forest is located 11.3 km north of Corvallis and is managed by Research Forest staff, College of Forestry, OSU. McDonald Forest is a teaching, research and demonstration forest revolving around four themes. These themes are:

⇒ Short Rotation Wood Production with High Return on Investment,
⇒ High Quality, Growth Maximizing Timber Production,
⇒ Visually Sensitive, Even-aged Forest,
⇒ Structurally Diverse Forest.

Biomass utilization is gaining interest in western Oregon and several biomass-powered cogeneration plants exist within 95 km of McDonald Forest. A major cost of biomass operations is the transportation cost. With small profit margins, it is important to determine the least cost method for transporting biomass from the woods to the mill. Being able to determine the optimal trucks and haul routes that would reduce total transportation costs would be important to the decision to utilize biomass. We applied the ACO heuristic to develop a least cost path from a sample of harvest units distributed through McDonald Forest. McDonald Forest is approximately 2,914 ha with 113 km of road or about 37.3 m of forest roads per hectare (Lysne D. and Klumph, B. OSU College Forests, Corvallis, Oregon, Personal Communication, December 14, 2011). The McDonald Forest road network and possible truck routes through Corvallis are shown in Fig. 6.

Thirty hypothetical timber harvests (sales) were spread through McDonald Forest (Fig. 6) for the purpose of reducing fuel loading around the urban interface. These timber harvests were assumed to produce and recover 89.7 green tonnes of biomass per hectare or 113.3 m^3 of biomass with 50 % moisture content. It was estimated that each sale would harvest between 45 and 95 ha (black triangles in Fig. 6). The destination node for all of the transported biomass is a biomass plant in Eugene (48 km south of Corvallis). The esti-

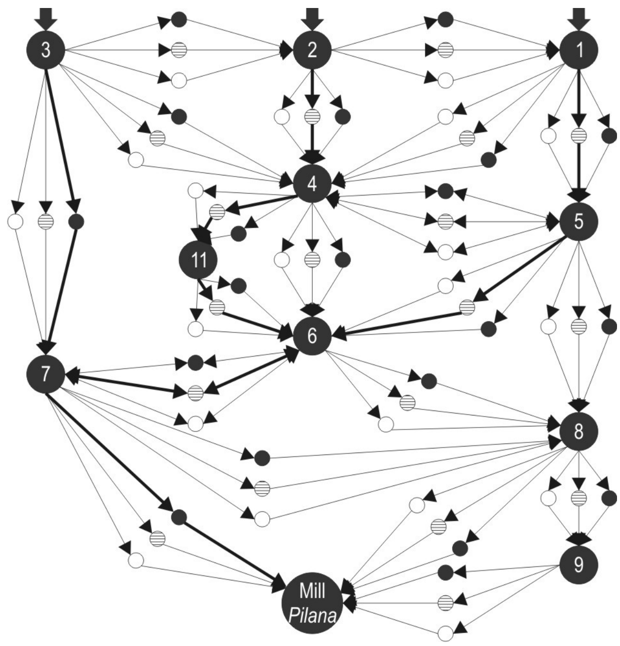

Fig. 5 Ant Colony Optimal Haul Routes. The bold arrows indicate optimal haul routes. The large black circles indicate nodes within the transportation network. The small black circles indicate the road modification option for the 16.2 m drop center 5th wheel chip van, the small horizontally hatched circles indicate the road modification option for the 13.7 m drop center 5th wheel chip van, and the small white circles indicate the road modification option for the stinger-steered chip van

Slika 5. *Optimalni pravac izvoženja prema metodi mravlje kolonije. Podebljane strelice označuju optimalni pravac izvoženja, dok veliki krugovi označuju raskrižja transportne mreže. Mali tamni kružići označuju šumsku cestu prilagođenu poluprikolici za šumsku sječku dugačkoj 16,2 m s utovarom na sredini, mali vodoravno iscrtkani kružići označuju šumsku cestu prilagođenu poluprikolici za šumsku sječku dugačkoj 13,7 s utovarom na sredini, dok mali bijeli kružići označuju šumsku cestu prilagođenu samokretnoj prikolici za šumsku sječku*

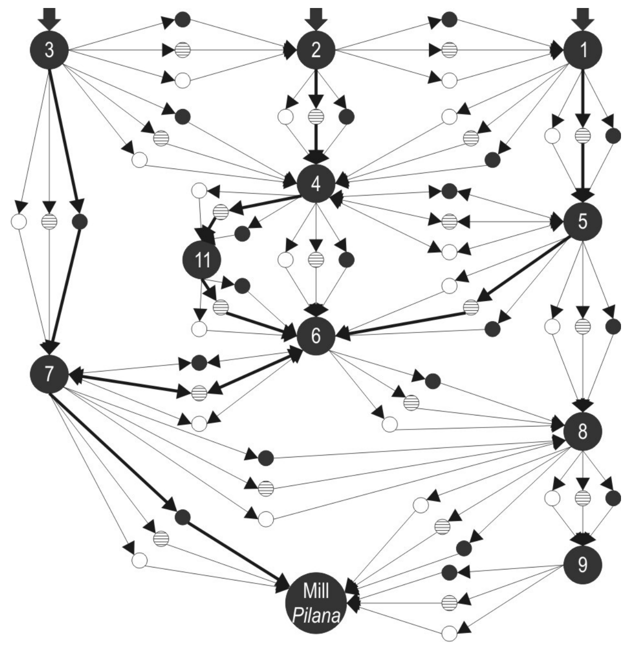

Fig. 6 Mixed Integer Optimal Haul Routes. The bold arrows indicate optimal haul routes. The large black circles indicate nodes within the transportation network. The small black circles indicate the road modification option for the 16.2 m drop center 5th wheel chip van, small horizontally hatched circles indicate the road modification option for the 13.7 m drop center 5th wheel chip van, and the small white circles indicate the road modification option for the stinger-steered chip van

Slika 6. *Optimalni pravac izvoženja prema metodi mješovitoga cjelobrojnoga linearnoga programiranja. Podebljane strelice označuju optimalni pravac izvoženja, dok veliki krugovi označuju raskrižja transportne mreže. Mali tamni kružići označuju šumsku cestu prilagođenu poluprikolici za šumsku sječku dugačkoj 16,2 m s utovarom na sredini, mali horizontalno iscrtkani kružići označujuju šumsku cestu prilagođenu poluprikolici za šumsku sječku dugačkoj 13,7 s utovarom na sredini, dok mali bijeli kružići označuju šumsku cestu prilagođenu samokretnoj prikolici za šumsku sječku*

mated travel speed on forest roads was 16.1 km/h and 72.4 km/h on major highways (loaded or unloaded). On public highways, it was assumed that any truck combination could be used without incurring any road modification costs.

The transportation network included 405 nodes and 2,433 links, including the existing transportation network and two modification options for each link. The existing transportation network was assumed to only permit stinger-steered trailer access. The other two trailer types required temporary road modification for access similar to the small network problem. The chip van operating characteristics in this problem are the same as Table 1. Once the chip vans were outside of the McDonald Forest, it was assumed that any chip van could be used without incurring a road modification cost. It was also assumed that adequate turnarounds exist to permit use of each truck type.

The routes for the 30 sales produced by the ACO in 10,000 iterations are shown in Fig. 8. For every sale, the ACO determined that the least cost path used a 16.2 m drop center 5th wheel chip van. The total transportation cost was $ 2,697,920 with $ 254,647 in road modification costs and $ 2,443,273 in haul costs. The road modification costs amount to 9 % of the total cost. If no road modifications had been made, only the

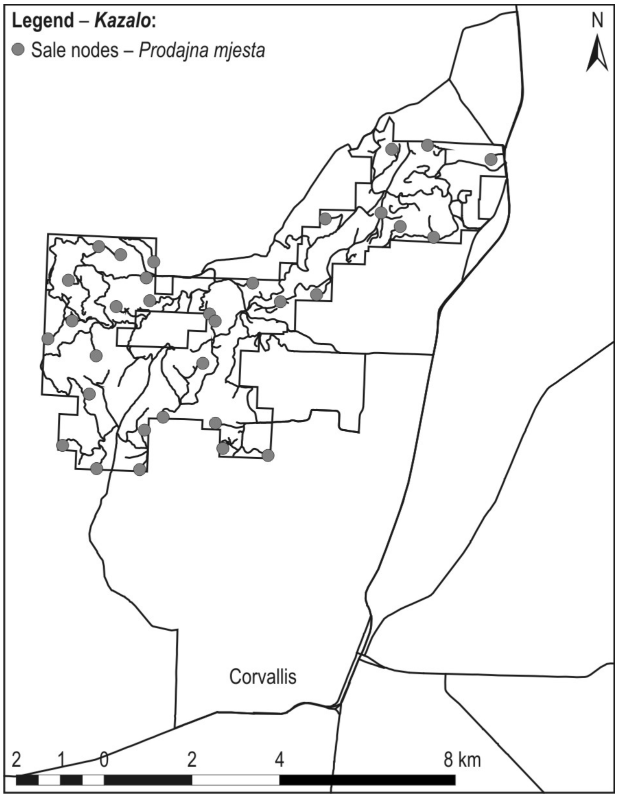

Fig. 7 McDonald Forest Road Network, Corvallis, Oregon, USA
Slika 7. *Mreža šumskih cesta u šumi »McDonald« Corvallis, Oregon, SAD*

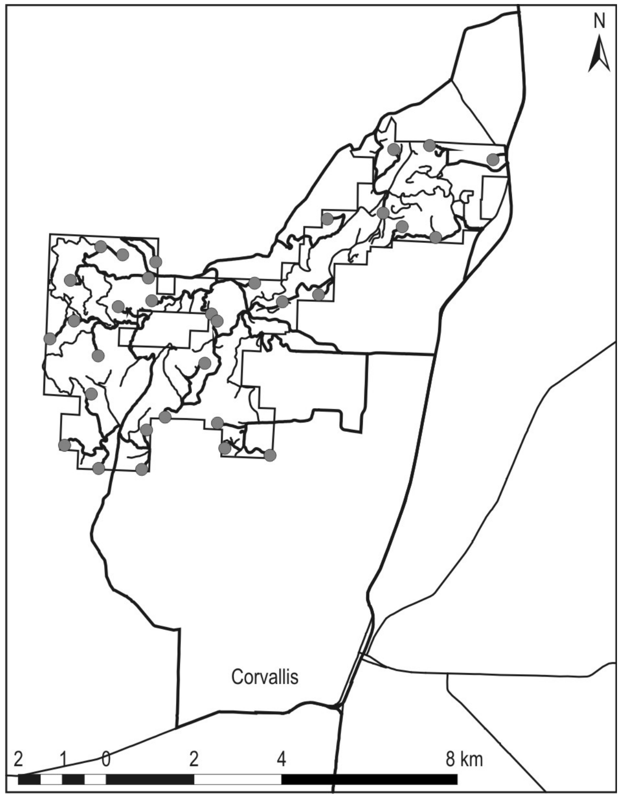

Fig. 8 Optimal route path for all 30 sales, McDonald Forest, Corvallis, Oregon, USA
Slika 8. *Optimalni pravac izvoženja za svih 30 turnusa u šumi »McDonald« Corvallis, Oregon, SAD*

stinger steered chip van could have been used with a total transportation cost of $ 3,703,310 (100 % haul costs). In this example, the ability to modify the roadway to allow larger trucks access to these sales reduced the total transportation cost by 27 %. The ability to reduce transportation costs by 27 % is a large benefit when margins are as slim as they are in the biomass market. This implies that being able to reduce the haul cost with the application of road modifications could have a significant positive impact.

7. Single Harvest Unit Analysis – Case Two – *Analiza pojedinačne sječine – slučaj prvi*

The network example provides an example of how several nearby chip or hog fuel sales and the use of road modifications can reduce overall transportation costs when considering road investments that benefit more than one sale. However, the ability to have nearby chip or hog fuel sales may not be practical. For the case of isolated sales, we provide a decision-making framework to assist in deciding the optimal truck type. When comparing cost per tonne versus highway haul kilometers, the 16.2 m drop center 5th wheel chip van is the most economical (Fig. 9). However, if the forest transportation network requires modification, the most economical chip van changes. For illustration, we assume that loaded and empty vehicles of a given type travel at the same speed and have the same hourly cost (Table 1). The cost per tonne including transport and road investment is:

$$Cost\ Per\ Ton_{\mathrm{t}} = \frac{2\times\ HK\times\ OC_{\mathrm{t}}}{KPH_{\mathrm{Ht}}\times\ VC_{\mathrm{t}}} + \frac{2\times\ FK\times OC_{\mathrm{t}}}{KPH_{\mathrm{Ft}}\times\ VC_{\mathrm{t}}} + \frac{FK\times PFK_{\mathrm{t}}\times\ MC_{\mathrm{t}}}{H\times\ V} \quad \forall\ t\in T \quad (9)$$

Where:

HK distance traveled on highway roads (one-way), km,

FK distance traveled on forest roads (one-way), km,

OC_t operating cost of chip van, t ($/hr),

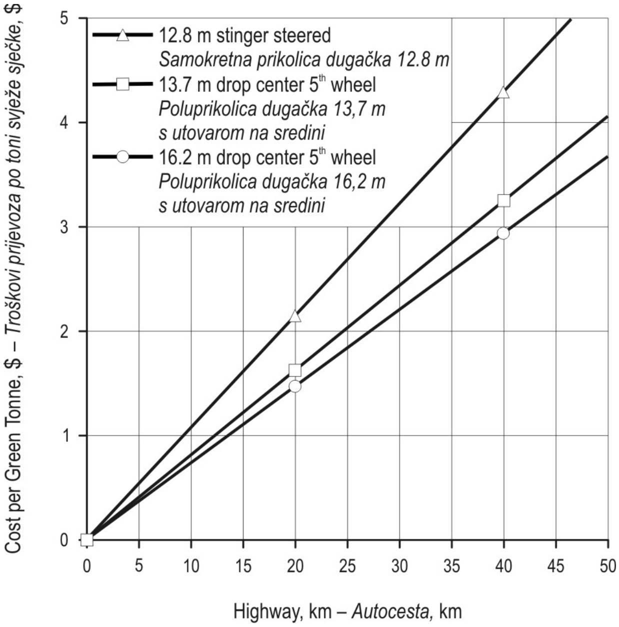

Fig. 9 Comparison of cost per tonne versus highway kilometers when traveling on highway roads. When traveling over highway roads or when traveling on the forest transportation network, where no modifications are required for all vehicles, the most economical chip van is the 16.2 m drop center 5th wheel chip van. On an 80 km highway haul, the cost savings is $ 2.71 per tonne comparing a 12.8 m stinger-steered chip van to a 16.2 m drop center 5th wheel chip van. We assumed each trailer is weight limited

Slika 9. *Usporedba troškova prijevoza po toni prema udaljenosti prijevoza autocestom. Prilikom prijevoza autocestom ili šumskim cestama gdje nije bilo potrebe za rekonstrukcijom najekonomičnijom se pokazala poluprikolica za šumsku sječku dugačka 16,2 m s utovarom na sredini. Na 80-om km autoceste ta je poluprikolica 2,71 $ po toni isplativija od samokretne prikolice za šumsku sječku dugačke 12,8 m uz pretpostavku poštivanja ograničenja nosivosti*

VC_t volume capacity of chip van, t,

KPH_{Ht} average operating speed on highway roads for chip van, t (km/h),

KPH_{Ft} average operating speed on forest roads for chip van, t (km/h),

PFK_t %age of the forest road kilometers that need to be modified for chip van, t,

MC_t forest road modification cost for chip van, t ($/km),

V harvest volume per hectare, tonnes/ha,

H total harvest area, ha.

Equation 9 can be manipulated to compare alternative truck options for the single sale. For example, the breakeven highway haul distance (the highway distance that provides the same cost per tonne between two trucking options) can be calculated for any two trucking options:

$$HM=\frac{FK\times\left(\frac{2\times OC_b}{KPH_{Fb}+VC_b}+\frac{PFK_b\times MC_b}{H\times V}-\frac{2\times OC_a}{KPH_{Fa}\times VC_a}-\frac{PKM_a\times MC_a}{H\times V}\right)}{\left(\frac{2\times OC_a}{KPH_{Ha}\times VC_a}-\frac{2\times OC_b}{KPH_{Hb}\times VC_b}\right)} \tag{10}$$

The subscripts »*a*« and »*b*« indicate the two trucking options being compared. Equation 10 assumes that both truck options can be operated on the highway. Some counties may have restrictions over some roads that do not permit trucks or trailer combinations over a maximum length or weight.

The breakeven equation between the 12.8 m stinger-steered chip van and the 16.2 m drop center 5th wheel chip van, if no road investment is required, is trivial (Fig. 9). The cost per tonne in the 16.2 m drop center 5th wheel chip van is always lower than the cost per tonne in the 12.8 m stinger-steered chip van.

The breakeven highway distance between the 12.8 m stinger-steered chip van and the 13.7 m drop center 5th wheel chip van for the 90 green tonnes of biomass per hectare case as a function of in forest kilometers (FK) is (operating characteristics from Table 1 were rounded for ease of illustration):

$$HM=\frac{FK\times\left(\frac{2\times\$91}{15\times29.9}+\frac{0.5\times3\,281}{90\times H}-\frac{2\times\$95}{15\times23.6}\right)}{\left(\frac{2\times\$95}{75\times23.6}-\frac{2\times\$91}{75\times29.9}\right)} \tag{11}$$

Equation (11) is the highway distance (km) needed to be traveled before the 13.7 m drop center 5th wheel chip van becomes economical for a given in forest hauling distance. The breakeven distance for a harvest area of 50 ha between these two vehicles for 2 km on forest roads is 17.8 highway km. For distances less than 17.8 km, it is more economical to use the 12.8 m stinger-steered chip van. For distances greater than 17.8 km and less than 179.4 km, it is more economical to use the 13.7 m drop center 5th wheel chip van (Fig. 10). A breakeven analysis of an in forest hauling distance of 15 km is shown in Fig. 11.

For the case of removing 45 green tonnes per hectare (such as a thinning operation) on a harvest unit of 50 ha and the in forest, hauling distance was either 2 km (Fig. 12) or 15 km (Fig. 13). The optimal trucking option would be the 12.8 m stinger-steered chip van for highway hauling distances less than 45.7 km, when hauling on 2 km of forest road and 342.6 km when hauling on 15 km of forest road. As volume removed is reduced, the use of road modifications to allow

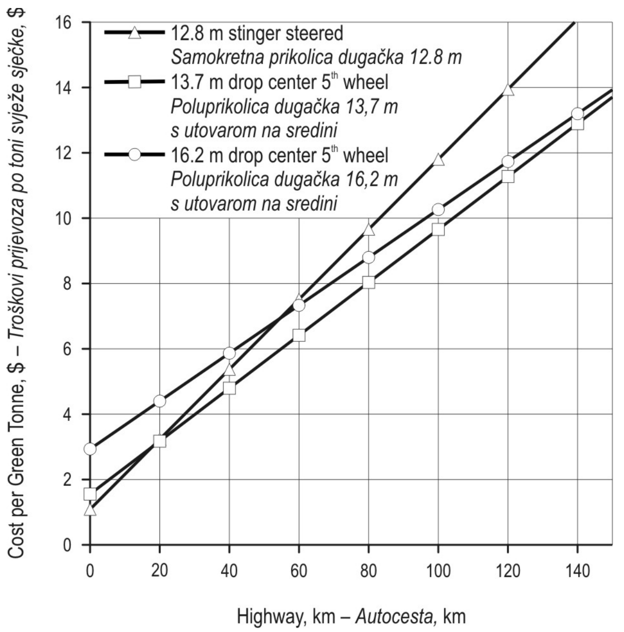

Fig. 10 Comparison of cost per tonne versus highway kilometers, when traveling over 2 km on forest road. This comparison uses 90 green tonnes per hectare for a 50 ha harvest unit. Modification costs are only applied to half of the distance traveled on a forest road. As the highway haul distance increases, a larger chip van becomes more economical. In this case, 17.8 km of highway hauling is the breakeven case between a 13.7 m drop center 5th wheel chip van and a 12.8 m stinger-steered chip van. The 16.2 m drop center 5th wheel chip van becomes economical over the 13.7 m drop center 5th wheel chip van at 179.4 km highway hauling

Slika 10. *Usporedba troškova prijevoza po toni prema udaljenosti prijevoza autocestom kada je vožnja šumskom cestom dulja od 2 km. Dobiveni podaci temelje se na sječnoj površini od 50 ha i 90 t svježe sječke po hektaru. Troškovi potrebni za rekonstrukciju šumskih cesta izračunavaju se za pola njihove duljine. S povećanjem udjela vožnje autocestom veća prikolica postaje ekonomičnija. U ovom slučaju na 17,8 km autoceste poluprikolica za šumsku sječku dugačka 13,7 m s utovarom na sredini postaje ekonomski isplativija od samokretne prikolice za šumsku sječku dugačke 12,8 m, dok poluprikolica za šumsku sječku dugačka 16,2 m s utovarom na sredini postaje ekonomski isplativija od poluprikolice za šumsku sječku dugačke 13,7 m s utovarom na sredini na 179,4 km autoceste*

larger vehicle access tends to increase transportation costs per tonne.

From the single harvest unit case, it is apparent that modifying the transportation network is not always the economical option. However, in the McDonald Forest transportation network example, it was cost efficient to modify the network to allow larger vehicles access. By grouping several biomass harvest units in close vicinity, the larger transport volume justifies a greater investment and makes a larger chip van economical.

8. Concluding Remarks – *Zaključna razmatranja*

Mixed integer programming and breakeven analysis have been applied for a long time to address forest transportation problems. The focus of this application has been in response to the worldwide interest in the utilization of forest residues for alternative energy. Unlike the primary log market, roads were not built to extract forest residues and the limited value of these

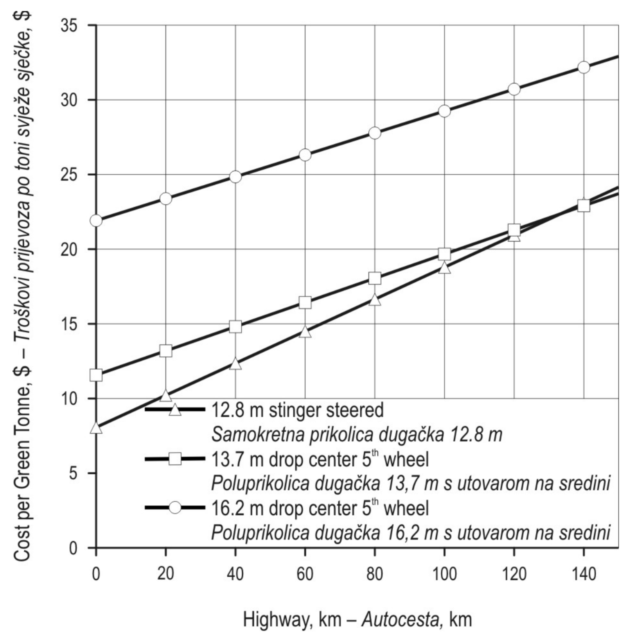

Fig. 11 Comparison of cost per tonne versus highway kilometers when each truck must travel 15 km on forest road. This comparison uses 90 green tonnes per hectare for a 50 ha harvest unit. Modification costs are only applied to half of the distance traveled on a forest road. As the highway haul distance increases, a larger chip van becomes more economical. In this case, 133.8 km of highway hauling is the breakeven case between a 13.7 m drop center 5th wheel chip van and a 12.8 m stinger-steered chip van

Slika 11. *Usporedba troškova prijevoza po toni prema udaljenosti prijevoza autocestom kada je vožnja šumskom cestom dulja od 15 km. Dobiveni podaci temelje se na sječnoj površini od 50 ha i 90 t svježe sječke po hektaru. Troškovi potrebni za rekonstrukciju šumskih cesta izračunaju se za pola njihove duljine. S povećanjem udjela vožnje autocestom veća prikolica postaje ekonomičnija. U ovom slučaju na 133,8 km autoceste poluprikolica za šumsku sječku dugačaka 13,7 m s utovarom na sredini postaje ekonomski isplativija od samokretne prikolice za šumsku sječku dugačke 12,8 m* products will usually not support widespread reconstruction of the forest network. However, strategic investments in the existing road network - some temporary, some permanent, may be justified. Decision support for temporary activities, such as filling ditches and changing road cross slopes to enable large vehicle access, has not been available in the literature.

When these ideas were applied to schedule multiple biomass operations over a common road network, the ACO heuristic obtained an optimal solution to a small problem; and when applied to a more realistic problem, quickly provided a solution. As transport volume increases, more could be spent on road modifications to allow larger truck capacity access. Being able to modify the forest transportation network to accommodate larger trucks access could greatly reduce hauling costs. Decisions for isolated biomass operations depend on road modification cost, transport volume, and transport costs on forest and highway roads. Breakeven analysis can be used to determine the optimal vehicle type. Further research is required to determine if the associated costs used in this paper accurately represent the road modification costs required to allow these non-standard trucks access.

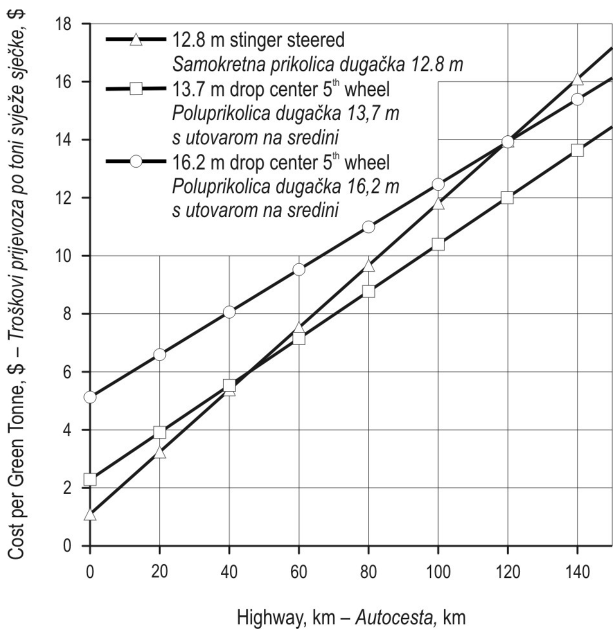

Fig. 12 Comparison of cost per tonne versus highway kilometers when traveling over 2 km on forest road. This comparison uses 45 green tonnes per hectare for a 50 ha harvest unit. Modification costs are only applied to half of the distance traveled on a forest road. As the highway haul distance increases, a larger chip van becomes more economical. In this case, 45.7 km of highway hauling is the breakeven case between a 13.7 m drop center 5th wheel chip van and a 12.8 m stinger-steered chip van. Not shown, the 16.2 m drop center 5th wheel chip van becomes economical over the 13.7 m drop center 5th wheel chip van at 368.9 km highway hauling

Slika 12. *Usporedba troškova prijevoza po toni prema udaljenosti prijevoza autocestom kada je vožnja šumskom cestom dulja od 2 km. Dobiveni podaci temelje se na sječnoj površini od 50 ha i 45 t svježe sječke po hektaru. Troškovi potrebni za rekonstrukciju šumskih cesta izračunaju se za pola njihove duljine. S povećanjem udjela vožnje autocestom veća prikolica postaje ekonomičnija. U ovom slučaju na 45,7 km autoceste poluprikolica za šumsku sječku dugačka 13,7 m s utovarom na sredini postaje ekonomski isplativija od samokretne prikolice za šumsku sječku dugačke 12,8 m, dok poluprikolica za šumsku sječku dugačka 16,2 m s utovarom na sredini postaje ekonomski isplativija od poluprikolice za šumsku sječku dugačke 13,7 m s utovarom na sredini na 368,9 km autoceste*

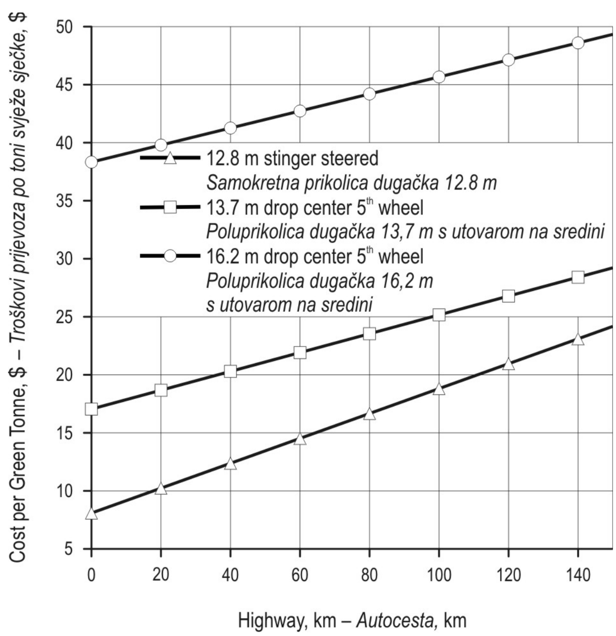

Fig. 13 Comparison of cost per tonne versus highway kilometers when traveling over 15 km on forest road. This comparison uses 45 green tonnes per hectare for a 50 ha harvest unit. Modification costs are only applied to half of the distance traveled on a forest road. As the highway haul distance increases, a larger chip van becomes more economical. In this case, the 12.8 m stinger-steered chip van is the most economical for highway hauling distances less than 342.6 km

Slika 13. *Usporedba troškova prijevoza po toni prema udaljenosti prijevoza autocestom kada je vožnja šumskom cestom dulja od 15 km. Dobiveni podaci temelje se na sječnoj površini od 50 ha i 45 t svježe sječke po hektaru. Troškovi potrebni za rekonstrukciju šumskih cesta izračunaju se za pola njihove duljine. S povećanjem udjela vožnje autocestom veća prikolica postaje ekonomičnija. U ovom slučaju samokretna prikolica za šumsku sječku dugačka 12,8 m najekonomičnija je do 342,6 km autoceste*

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Appendix – *Dodatak*

Table 5 Haul and Modification Cost for the Small Network
Tablica 5. *Troškovi prijevoza i rekonstrukcije*

Link Identifier *Šifre pravaca izvoženja*		Truck Type *Vrsta prikolice*	Round Trip Haul Cost, $/Truck/Link *Troškovi prijevoza po turnusu, $/prikolica/pravac*	Modification Cost, $/Link *Troškovi rekonstrukcije, $/pravac*
From – *Od*	To – *Do*			
1	4	12.8 m Stinger *Samokretna prikolica dugačka 12,8 m*	18.79	0
1	4	13.7 m Drop Center 5th wheel *Poluprikolica dugačka 13,7 m s utovarom na sredini*	17.91	2,600
1	4	16.2 m Drop Center 5th wheel *Poluprikolica dugačka 16,2 m s utovarom na sredini*	19.66	7,800
1	5	12.8 m Stinger *Samokretna prikolica dugačka 12,8 m*	6.14	0
1	5	13.7 m Drop Center 5th wheel *Poluprikolica dugačka 13,7 m s utovarom na sredini*	5.86	850
1	5	16.2 m Drop Center 5th wheel *Poluprikolica dugačka 16,2 m s utovarom na sredini*	6.43	2,550
2	1	12.8 m Stinger *Samokretna prikolica dugačka 12,8 m*	12.28	0
2	1	13.7 m Drop Center 5th wheel *Poluprikolica dugačka 13,7 m s utovarom na sredini*	11.71	1,700
2	1	16.2 m Drop Center 5th wheel *Poluprikolica dugačka 16,2 m s utovarom na sredini*	12.85	5,100
2	4	12.8 m Stinger *Samokretna prikolica dugačka 12,8 m*	6.14	0
2	4	13.7 m Drop Center 5th wheel *Poluprikolica dugačka 13,7 m s utovarom na sredini*	5.86	850

2	4	16.2 m Drop Center 5th wheel *Poluprikolica dugačka 16,2 m s utovarom na sredini*	6.43	2,550
3	2	12.8 m Stinger *Samokretna prikolica dugačka 12,8 m*	9.39	0
3	2	13.7 m Drop Center 5th wheel *Poluprikolica dugačka 13,7 m s utovarom na sredini*	8.96	1,300
3	2	16.2 m Drop Center 5th wheel *Poluprikolica dugačka 16,2 m s utovarom na sredini*	9.83	3,900
3	4	12.8 m Stinger *Samokretna prikolica dugačka 12,8 m*	6.50	0
3	4	13.7 m Drop Center 5th wheel *Poluprikolica dugačka 13,7 m s utovarom na sredini*	6.20	900
3	4	16.2 m Drop Center 5th wheel *Poluprikolica dugačka 16,2 m s utovarom na sredini*	6.80	2,700
3	7	12.8 m Stinger *Samokretna prikolica dugačka 12,8 m*	6.32	0
3	7	13.7 m Drop Center 5th wheel *Poluprikolica dugačka 13,7 m s utovarom na sredini*	6.03	875
3	7	16.2 m Drop Center 5th wheel *Poluprikolica dugačka 16,2 m s utovarom na sredini*	6.61	2,625
4	5	12.8 m Stinger *Samokretna prikolica dugačka 12,8 m*	9.03	0
4	5	13.7 m Drop Center 5th wheel *Poluprikolica dugačka 13,7 m s utovarom na sredini*	8.61	1,250
4	5	16.2 m Drop Center 5th wheel *Poluprikolica dugačka 16,2 m s utovarom na sredini*	9.45	3,750
4	6	12.8 m Stinger *Samokretna prikolica dugačka 12,8 m*	6.14	0
4	6	13.7 m Drop Center 5th wheel *Poluprikolica dugačka 13,7 m s utovarom na sredini*	5.86	850
4	6	16.2 m Drop Center 5th wheel *Poluprikolica dugačka 16,2 m s utovarom na sredini*	6.43	2,550
4	11	12.8 m Stinger *Samokretna prikolica dugačka 12,8 m*	4.34	0

4	11	13.7 m Drop Center 5th wheel *Poluprikolica dugačka 13,7 m s utovarom na sredini*	4.13	600
4	11	16.2 m Drop Center 5th wheel *Poluprikolica dugačka 16,2 m s utovarom na sredini*	4.54	1,800
5	4	12.8 m Stinger *Samokretna prikolica dugačka 12,8 m*	7.95	0
5	4	13.7 m Drop Center 5th wheel *Poluprikolica dugačka 13,7 m s utovarom na sredini*	7.58	1,100
5	4	16.2 m Drop Center 5th wheel *Poluprikolica dugačka 16,2 m s utovarom na sredini*	8.32	3,300
5	6	12.8 m Stinger *Samokretna prikolica dugačka 12,8 m*	3.61	0
5	6	13.7 m Drop Center 5th wheel *Poluprikolica dugačka 13,7 m s utovarom na sredini*	3.45	500
5	6	16.2 m Drop Center 5th wheel *Poluprikolica dugačka 16,2 m s utovarom na sredini*	3.78	1,500
5	8	12.8 m Stinger *Samokretna prikolica dugačka 12,8 m*	6.14	0
5	8	13.7 m Drop Center 5th wheel *Poluprikolica dugačka 13,7 m s utovarom na sredini*	5.86	850
5	8	16.2 m Drop Center 5th wheel *Poluprikolica dugačka 16,2 m s utovarom na sredini*	6.43	2,550
6	7	12.8 m Stinger *Samokretna prikolica dugačka 12,8 m*	5.42	0
6	7	13.7 m Drop Center 5th wheel *Poluprikolica dugačka 13,7 m s utovarom na sredini*	5.17	750
6	7	16.2 m Drop Center 5th wheel *Poluprikolica dugačka 16,2 m s utovarom na sredini*	5.67	2,250
6	8	12.8 m Stinger *Samokretna prikolica dugačka 12,8 m*	6.50	0
6	8	13.7 m Drop Center 5th wheel *Poluprikolica dugačka 13,7 m s utovarom na sredini*	6.20	900
6	8	16.2 m Drop Center 5th wheel *Poluprikolica dugačka 16,2 m s utovarom na sredini*	6.80	2,700

7	6	12.8 m Stinger *Samokretna prikolica dugačka 12,8 m*	1.81	0
7	6	13.7 m Drop Center 5th wheel *Poluprikolica dugačka 13,7 m s utovarom na sredini*	1.72	250
7	6	16.2 m Drop Center 5th wheel *Poluprikolica dugačka 16,2 m s utovarom na sredini*	1.89	750
7	8	12.8 m Stinger *Samokretna prikolica dugačka 12,8 m*	6.50	0
7	8	13.7 m Drop Center 5th wheel *Poluprikolica dugačka 13,7 m s utovarom na sredini*	6.20	900
7	8	16.2 m Drop Center 5th wheel *Poluprikolica dugačka 16,2 m s utovarom na sredini*	6.80	2,700
7	10	12.8 m Stinger *Samokretna prikolica dugačka 12,8 m*	9.03	0
7	10	13.7 m Drop Center 5th wheel *Poluprikolica dugačka 13,7 m s utovarom na sredini*	8.61	0
7	10	16.2 m Drop Center 5th wheel *Poluprikolica dugačka 16,2 m s utovarom na sredini*	9.45	0
8	9	12.8 m Stinger *Samokretna prikolica dugačka 12,8 m*	5.06	0
8	9	13.7 m Drop Center 5th wheel *Poluprikolica dugačka 13,7 m s utovarom na sredini*	4.82	700
8	9	16.2 m Drop Center 5th wheel *Poluprikolica dugačka 16,2 m s utovarom na sredini*	5.29	2,100
8	10	12.8 m Stinger *Samokretna prikolica dugačka 12,8 m*	19.51	0
8	10	13.7 m Drop Center 5th wheel *Poluprikolica dugačka 13,7 m s utovarom na sredini*	18.60	0
8	10	16.2 m Drop Center 5th wheel *Poluprikolica dugačka 16,2 m s utovarom na sredini*	20.41	0
9	10	12.8 m Stinger *Samokretna prikolica dugačka 12,8 m*	9.03	0
9	10	13.7 m Drop Center 5th wheel *Poluprikolica dugačka 13,7 m s utovarom na sredini*	8.61	0
9	10	16.2 m Drop Center 5th wheel *Poluprikolica dugačka 16,2 m s utovarom na sredini*	9.45	0
11	6	12.8 m Stinger *Samokretna prikolica dugačka 12,8 m*	0.36	0
11	6	13.7 m Drop Center 5th wheel *Poluprikolica dugačka 13,7 m s utovarom na sredini*	0.34	50
11	6	16.2 m Drop Center 5th wheel *Poluprikolica dugačka 16,2 m s utovarom na sredini*	0.38	150

Sažetak

Odlučivanje o izvoznim pravcima prikolica za šumsku sječku uz optimizaciju metodom mravlje kolonije i analizu prekretnice troškova

Nekonvencionalni (sekundarni) šumski proizvodi pružaju mogućnost povećanja ekonomske vrijednosti šume, dok transport takvih proizvoda u nekim slučajevima zahtijeva prijevoz specijaliziranim vozilima. Zbog činjenice da postojeća šumska prometna infrastruktura uglavnom nije dizajnirana prema standardima koje specijalizirana vozila zahtijevaju potrebno je raditi izmjene (rekonstrukcije) na šumskim cestama (zatrpavanje odvodnih jaraka, proširivanje i rekonstruiranje kolničke konstrukcije) kako bi se takvim vozilima omogućio pristup šumi. Svaku izmjenu kolničke konstrukcije potrebno je prilagoditi tehničkim karakteristikama specijaliziranih vozila koja će naposljetku tom šumskom cestom i prometovati. U ovom su radu promatrani različiti transportni sustavi za (1) višestruko izvoženje biomase, (2) pojedinačno izvoženje biomase.

U slučaju višestrukoga izvoženja biomase primijenjena je metoda mješovitoga cjelobrojnoga linearnoga programiranja i metoda temeljena na principu mravlje kolonije »Ant Colony Optimization« (ACO). Obje su metode korištene na malom uzorku prikazanom na slici 4. Jedina razlika između tih dviju metoda iznosi $ 13, a nastala je tijekom izračuna (zaokruživanja) kod metode mješovitoga cjelobrojnoga linearnoga programiranja (tablice 3 i 4). Metoda ACO primijenjena je pri određivanju optimalnoga specijaliziranoga vozila (prikolice) te pri izboru optimalnoga pravca izvoženja za 30 hipotetski odabranih mjesta iverenja u šumama »McDonald« u Corvallisu, Oregon, Sjedinjene Američke Države (slika 7). Metodom ACO utvrđeno je da su ukupni troškovi prijevoza najmanji prilikom korištenja najveće prikolice za šumsku biomasu, što razumijeva najveću rekonstrukciju šumske ceste na pravcima izvoženja. Na dionicama gdje nije bila potrebna izmjena kolničke konstrukcije ukupni troškovi prijevoza manji su za 27 %.

Pri pojedinačnom izvoženju biomase primijenili smo prikladniju analizu prekretnice troškova. Analiza prekretnice troškova pretpostavlja da su pravci izvoženja poznati, dok su varijable operativne karakteristike prikolice za šumsku biomasu te troškovi izgradnje pripadajuće šumske ceste s uračunatim troškovima rekonstrukcije šumske ceste (jednadžba 9). Pomoću jednadžbe 10 može se utvrditi na kojoj su udaljenosti (autoceste) troškovi transporta kod promatranih dviju opcija jednaki. U ovom smo radu procijenili četiri različita slučaja, čistu sječu i prorede s kratkim i dugim duljinama privlačenja. Utvrđeno je da se zbog povećanja privlačenja drvnih sortimenata te zbog potreba za izmjenom kolničke konstrukcije pri korištenju većega kamiona nadmašuje korisnost povećanoga obujma biomase po tovaru većega kamiona. Osim toga, zbog smanjenja obujma biomase po hektaru (proreda) te troškova rekonstrukcije pojedine šumske ceste potreban je dulji transport autocestom (veća udaljenost) da bi veći kamion bio ekonomičan. Ovom je analizom utvrđeno da rekonstrukcija šumskih cesta nije uvijek ekonomičan izbor.

Ključne riječi: optimizacija metodom mravlje kolonije, transport šumske biomase, pristupačnost vozilima

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