Original scietific paper – *Izvorni znanstveni rad*

Predicting and Controlling Moisture Content to Optimise Forest Biomass Logistics

Mauricio Acuna, Perttu Anttila, Lauri Sikanen, Robert Prinz, Antti Asikainen

Abstract – Nacrtak

Wood fuel quality attributes have to be considered by logistics planners if fuel procurement from forests and energy production at the plant are considered simultaneously. The single most important quality attribute is the moisture content (MC) of chips or raw material delivered to energy plants. It affects heating value, storage properties, chipping and transport costs of the fuel. To assess the impact of forest biomass moisture content on supply chain costs, we developed a linear programming-based tool for optimization decision support that minimizes supply chain costs including harvesting, storage, chipping, and transportation of fuels. A CHP plant in Finland was used as the study case and three biomass raw materials (supply chains) were used for the analysis: whole trees from early thinnings, stemwood from early thinnings, and logging residues from final fellings. Our results indicate that both the proportion and volume of the biomass material delivered to the plant are very sensitive to specifications on MC range limits and the length of the storage (drying) period. Compared to a scenario with no storage, a reduction in volume harvested of up to 33% can be achieved to meet the monthly energy demand if proper drying methods, such as covering of biomass material, are implemented before chipping and delivering the biomass materials to the energy plant.

Keywords: moisture content, biomass supply chain, optimal storage and transportation, linear programming, biomass covering

1. Introduction – *Uvod*

To sustainably meet the increasing demand for forest biomass, proper harvesting technology (including comminution, handling and storage) and work methods must be developed and implemented with the goal to produce high quality fuels (Röser et al. 2010). Fuel quality is assessed based on the properties that affect the energy yield and costs. Moisture content (MC), gross calorific value and ash content of the logging residue are three properties commonly used to assess the fuel quality, as each of these properties determine the viability of biomass procurement for energy production (Gautam et al. 2012; Brand et al. 2011), as well as the usability of the plant and efficiency and economy of combustion (Röser et al. 2011). The most important single quality factor is the MC of chips. It affects the heating value, storage properties and transport costs of the fuel (Asikainen et al. 2001; Röser et al. 2011). MC is a direct cost factor, and it is taken into account in the pricing of the fuel. An excessive MC results in a price reduction, while a low MC brings a bonus.

The procurement of logging residue for energy production can be uneconomical due to high MC and low calorific value. High MC in biomass lowers the energy density and transportation becomes less efficient (Gautam et al. 2012). Therefore, natural drying of timber during the procurement processes should be promoted to facilitate the drying process and ensure the availability of high quality fuel in the short and long term (Röser et al. 2011). Some considerations have to be made by logistics planners if fuel procurement from forests and energy production at the plant are considered simultaneously. On one hand the extension of storage time lowers system costs by lowering transportation costs and by improving efficiency at the plant. The efficiency improvement is the result of increasing heating value and lower needle and impurity content in the material. On the other hand, extension of storage time increases system costs because the wood starts to decompose causing material losses and because of the capital invested in the stored fuel (Asikainen et al. 2001; Pettersson and Nordfjell 2007).

Drying (MC) curves are a vital piece of information when implementing optimal storage, harvesting, chipping and transportation decisions in a biomass planning model. Although mathematical models have been developed to optimize biomass logistics for short periods (Eriksson and Bjorheden 1989; Gunnarson et al. 2004; Kanzian et al. 2009), we are not aware of any logistics model or study that investigated the effect of MC on supply chain costs for longer periods (> 1 year) through the use of an optimization model that explicitly uses MC as an input parameter. Taking previous studies as a reference point, we developed a linear programming-based decision support tool to conduct an investigation into the effect of biomass MC on supply chain costs for an operational planning under different scenarios.

2. Materials and methods – *Materijal i metode*

2.1 Supply chains used for the analysis – *Lanci dobave*

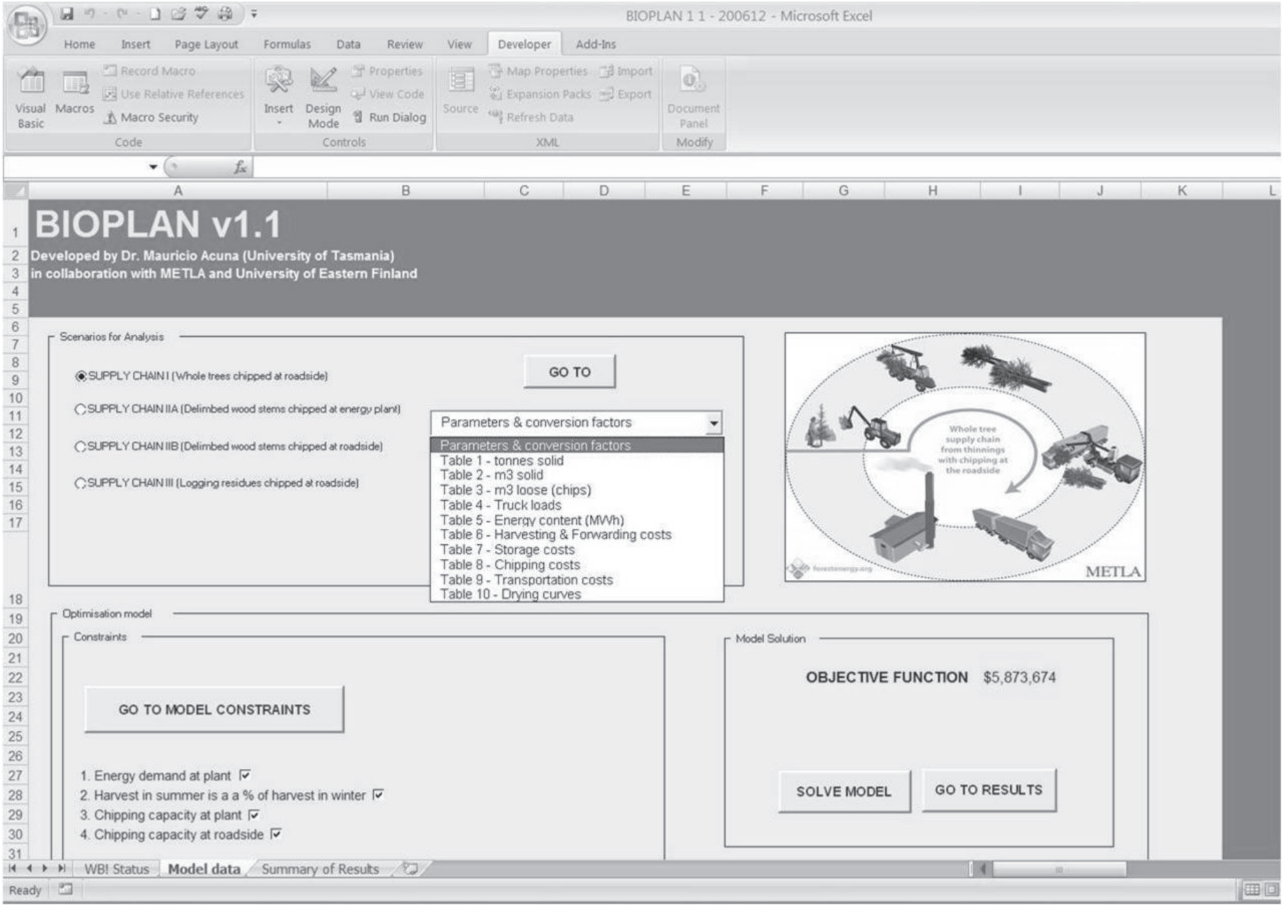
The study is based on the parameters of a large scale combined heat and power plant (CHP) in Joensuu, Finland, and the described supply chains apply to the Joensuu facility. This plant has a total CHP output of 180 MW, out of which 30 MW is electrical output. The produced heat is distributed to the city through a district heating (DH) system. In the DH area of Joensuu, 41 640 inhabitants (or 57% of the municipality population) are connected to the 200 km pipeline DH network (Energiateollisuus 2011).

In our study, a number of forest energy supply chains were selected and included in the optimization logistics model. The biomass materials selected and their corresponding supply chains were adapted and simplified to meet the objectives of the investigation using the Joensuu CHP plant study case.

Supply chain I: Whole tree supply chain from thinnings with chipping at the roadside. In Finland, logging systems in small diameter whole tree thinning can be classified into those based on the motor-manual or mechanized cutting of trees. Supply chain I is based on the traditional two machine system with a harvester and a forwarder, where both machines utilize the multi-tree processing technique. Since the felling phase is still the most demanding and costly part of the production chain in energy thinning, the cutting of whole trees can be done with purpose built accumulating felling heads or by normal harvester heads equipped with multi-tree handling accessories (Laitila 2012). After felling, thinning trees are forwarded to roadside where they are left (stored) to dry for a few months. In the last step, comminution of whole trees is done at the roadside using heavy truck-mounted chippers or crushers in large-scale operations. To avoid delays caused by the interaction of machines, the truck mounted chipper and chip truck can be replaced by a single chipper truck. That blows the chips directly into a container and then hauls the load to the plant. As the chipper truck is equipped with its own chipping device and crane, load capacity suffers and the operation radius around the plant is reduced (Hakkila 2004).

Supply chain II: Delimbed stems from thinnings with chipping at the plant. The harvesting units are equipped with delimbing knives and feed rollers that are suitable for multiple-tree processing (Laitila 2012). The costs of multi-stem harvesting to produce delimbed shortwood are, on average, 23% greater than harvesting whole trees due to the difference in productivity (Heikkilä et al. 2005; Laitila et al. 2010; Laitila and Väätäinen 2011). In this supply chain, logging residues (branches, needles, etc.) are left in the stand, and only the delimbed stems are forwarded to roadside for storage. Wood stems are dried for a few months at the roadside after which they are transported to the plant for comminution. This is performed using highly efficient chippers or crushers which makes road transportation and chipping operations independent of each other and very cost efficient, especially with short transportation distances. This provides some advantages such as increased technical and operative availability of the equipment, an independent and less labor intensive procurement process and the improvement of fuel quality (Hakkila 2004).

Supply chain III. Logging residues with chipping at roadside. In Finland, logging residues are obtained primarily during final fellings conducted each year from November to March (winter months). In this case, the procurement of logging residues is based on the loose residue system. The harvesting method is adapted so that logging residues are left (stored) in the stand during the timber processing. After drying, the logging residues are forwarded to roadside, normally by a forwarder with an enlarged load space and a residue grapple. In a next step, the logging residues are comminuted at the roadside landing close to the logging site in a similar fashion to supply chain I.



BIOPLAN v1.1

Developed by Dr. Mauricio Acuna (University of Tasmania)
in collaboration with METLA and University of Eastern Finland

● SUPPLY CHAIN I (Whole trees chipped at roadside)
○ SUPPLY CHAIN IIA (Delimbed wood stems chipped at energy plant)
○ SUPPLY CHAIN IIB (Delimbed wood stems chipped at roadside)
○ SUPPLY CHAIN III (Logging residues chipped at roadside)

1. Energy demand at plant ☑
2. Harvest in summer is a a % of harvest in winter ☑
3. Chipping capacity at plant ☑
4. Chipping capacity at roadside ☑

OBJECTIVE FUNCTION $5,873,674

Fig. 1 BIOPLAN 1.1 user's interface

Slika 1. *Računalni program BIOPLAN 1.1 – sučelje*

2.2 Biomass supply chain optimization system *Optimizacija sustava dobave biomase*

2.2.1 Implementation of the system – *Primjena sustava*

We developed and implemented a linear programming, MS Excel©-based tool for optimization decision support named BIOPLAN to investigate the effect of MC on storage, chipping and transportation costs of biomass material delivered to an energy plant (Fig. 1). The objective function of the strategic, non-spatial optimization model minimizes the total costs associated with harvesting, storage, chipping and transport according to MC curves, which are included as explicit parameters in the optimization model.

In its current version (1.1), BIOPLAN includes whole trees from thinning, delimbed stems from thinning, and logging residues as biomass materials along with their corresponding supply chains. BIOPLAN is structured in such a way that all the information is displayed in a series of matrices which include:

- ⇒ Decision variables on tons and corresponding solid volume of biomass material to harvest in each period,
- ⇒ Loose volume of wood chips produced in each period (roadside or energy plant),
- ⇒ Number of truck loads delivered to the energy plant,
- ⇒ Energy content of chips,
- ⇒ Harvesting and forwarding costs (including subsidies for whole trees and stem wood from thinning operations), chipping costs (roadside or energy plant), storage cost of material at the roadside, and transportation cost (stemwood or chips).

The model considers a 2-year planning horizon and decisions on tons or volume of biomass material to harvest are made on a monthly basis (24 periods) over that time horizon. Except in supply chain II, the biomass material is stored for a number of periods and then chipped at the roadside. Chips with a determined

Table 1 Sets, parameters, and variables used in the mathematical formulation of the model

Tablica 1. *Grupe, parametri i varijable primijenjeni u matematičkom formuliranju modela*

Term – *Termin*	Definition – *Definicija*
Set – *Grupa*	Set – *Grupa*
i,j = periods	$i \in I = \{1...24\}$, $j \in J = \{13...24\}$
	Parameters – *Parametri*
α, β, γ	Conversion factors from m^3 solid to m^3 loose for whole trees, stem wood and logging residues, respectively *Faktori pretvorbe iz rasute u čvrstu drvnu tvar dobivenu od cijelih stabala, debla i drvnoga ostataka*
$EC_{wt}, EC_{sw}, EC_{lr}$	Energy content for chips produced from whole trees, stem wood and logging residues, respectively *Energija iz iverja cijelih stabala, debla i drvnoga ostatka*
$HC_1^{wt}, HC_1^{sw}, HC_1^{lr}$	Harvesting cost (€/m^3 solid) for whole trees, stem wood, and logging residues harvested in period *i* *Troškovi sječe (€/m^3 čvrste tvari) za cijela stabla, debla i šumski ostatak u godini* i
$ST_{1,j}^{wt}, ST_{1,j}^{sw}, ST_{1,j}^{lr}$	Storage cost (€/m^3 solid) for whole trees, stem wood, and logging residues stored at roadside from period *i* to *j* ($i \le j$) *Troškovi skladištenja uz šumsku cestu (€/m^3 čvrste tvari) za cijela stabla, debla i šumski ostatak u vremenu od* i *do* j (i ≤ j)
$CH_{1,j}^{wt}, CH_{1,j}^{sw}, CH_{1,j}^{lr}$	Chipping cost (€/m^3 solid) for whole trees, stem wood, and logging residues harvested in period *i* and chipped in period *j* at roadside or plant *Troškovi iveranja (€/m^3 čvrste tvari) cijelih stabala, debala i drvnoga ostatka, sječenih u vremenu* i, *iveranih uz šumsku cestu ili u energani, u vremenu* j
$TR_{1,j}^{wt}, TR_{1,j}^{sw}, TR_{1,j}^{lr}$	Transportation cost (€/m^3) for whole trees chips (solid volume), stem wood (solid volume), and logging residues chips (loose volume) harvested in period *i* and transported to plant in period *j* *Troškovi prijevoza iverja (€/m^3) cijelih stabala (čvrsta tvar), debala (čvrsta tvar) i drvnoga ostatka (rasuta tvar) posječenih u vremenu* i *te prevezenih u energanu u vremenu* j
	Variables – *Varijable*
$x_{i,j}$	Solid volume of whole trees harvested in period *i* and stored at roadside until period *j* for chipping *Obujam čvrste tvari iz cijelih stabala posječenih u vremenu* i *te skladištenih uz šumsku cestu do vremena iveranja* j
$y_{i,j}$	Solid volume of stem wood trees harvested in period *i* and stored at roadside until period *j* for transport and chipping at the plant *Obujam čvrste tvari iz deblovine pridobivene u vremenu* i *te skladištenih uz šumsku cestu do vremena* j *uz iveranje u energani*
$z_{i,j}$	Solid volume of logging residues harvested in period *i* and stored at roadside until period *j* for chipping *Obujam čvrste tvari iz drvnoga ostatka pridobivenoga u vremenu* i *te uskladištenoga uz šumsku cestu do vremena iveranja* j
$x_{i,j}^r$	$x_{i,j} \times \alpha$ = Loose volume of chips from whole trees harvested in period *i* and stored at roadside until period *j* for chipping $x_{i,j} \times \alpha$ = *Obujam rasutoga iverja dobivenoga iz cijelih stabala posječenih u vremenu* i *te uskladištenih uz šumsku cestu do vremena iveranja* j
$z_{i,j}^r$	$z_{i,j} \times \gamma$ = Loose volume of chips from logging residues harvested in period *i* and stored at roadside until period *j* for chipping $z_{i,j} \times \gamma$ = *Obujam rasutoga iverja dobivenoga iz drvnoga ostatka u vremenu* i *te uskladištenoga uz šumsku cestu do vremena iveranja* j

moisture and energy content are then transported to the energy plant for consumption. In supply chain II, stemwood is stored at the roadside for a number of periods and then transported to the energy plant for chipping and consumption. Storage of any biomass material at the roadside is allowed for a period of up to 24 months (from January Year 1 to December Year 2) and all the material supplied must meet the plant monthly demand for energy (MWh) in the year 2 (Energy Generation Year) at minimum cost. That means that any biomass produced in the year 1 will be combusted in the year 2. In its basic formulation, the supply chain model can be expressed as follows. Sets, parameters, and variables are presented in Table 1:

Objective function (FO)

Equation 1 minimizes the total supply chain costs (€), associated with biomass harvesting, storage, chipping and transport.

$$FO = \sum_{i,j} X_{i,j} * \left(HC_{i}^{wt} + ST_{i,j}^{wt} + CH_{i,j}^{wt}\right) + \sum_{i,j} X'_{i,j} * TR_{i,j}^{wt} + \sum_{i,j} Y_{i,j} * \left(HC_{i}^{sw} + ST_{i,j}^{sw} + CH_{i,j}^{sw} * TR_{i,j}^{sw}\right) + \sum_{i,j} Z_{i,j} * \left(HC_{i}^{lr} + ST_{i,j}^{lr} + CH_{i,j}^{lr}\right) + \sum_{i,j} Z'_{i,j} * TR_{i,j}^{lr} \quad (1)$$

Constraints

Equation 2 ensures that the energy content of the chips supplied satisfy the monthly energy demand at the plant (MWh).

$$\sum_{i \le j} X'_{i,j} * EC_{i,j}^{wt} + \sum_{i \le j} Y'_{i,j} * EC_{i,j}^{sw} + \sum_{i \le j} Z'_{i,j} * EC_{i,j}^{lr} \ge ED_{j} \quad \forall j \in J \quad (2)$$

Equation 3 ensures that an even volume of whole trees is harvested evenly in each year. This allows for continuous work for the harvesting and haulage contractors.

$$\sum_{j} X_{i,j} = \sum_{j} X_{i+1,j} \quad \forall i \in \{1 \dots 11, 13 \dots 23\} \quad (3)$$

Equation 4 ensures that an even volume of stem wood is harvested evenly each year. This allows for continuous work for the harvesting and haulage contractors.

$$\sum_{j} Y_{i,j} = \sum_{j} Y_{i+1,j} \quad \forall i \in \{1 \dots 11, 13 \dots 23\} \quad (4)$$

Equation 5 ensures that an even volume of logging residues is harvested evenly during the winter months of each year.

$$\sum_{j} Z_{i,j} = \sum_{j} Z_{i+1,j} \quad \forall i \in \{3 \dots 10, 15 \dots 23\} \quad (5)$$

The model assumes that in any period the chips arriving at the energy plant must be consumed in the same period, and therefore, there are no costs associated with the storage of chips at the plant. Other constraints modeled in the system include MC limits for chips and stemwood arriving at the plant, and drying period limits for the materials that are stored at the roadside. Stumpage price is not included as part of the total supply chains costs.

As outputs, BIOPLAN reports total cost for the whole operation and total cost by activity (harvesting, storage, chipping, and transportation), as well as total energy of the fuel supplied to the plant in MWh. Additionally, for each supply chain, the system reports solid volume and fresh tons of biomass material harvested, loose volume of chips produced at the roadside or plant, total energy content (MWh), and total number of truck loads with chips or stem wood arriving at the plant. Within each supply chain, the system reports the cost per m^3 solid, cost per green ton, cost per m^3 loose, cost per truck load and cost per MWh.

2.2.2 Optimization model parameters – *Parametri optimizacijskoga modela*

Table 2 shows the parameters used in the control scenario for the three supply chains analysed.

Several references were consulted to get the parameters for BIOPLAN. Basic density, calorific values, and solid content for the main species in Finland were obtained from Nurmi (1993); Hakkila (2004); and Laurila and Lauhanen (2012). Harvesting, chipping, and transport costs are presented in Table 3. These costs were preliminarily calculated and validated from costing spreadsheets developed by METLA (Heikkila et al. 2005; Laitila 2006; Laitila 2008). These values were subsequently updated by using results from more recent studies (Laitila et al. 2010; Laitila and Väätäinen

Table 2 Parameters and conversion factors used in BIOPLAN

Tablica 2. *Paramateri i faktori pretvorbe primijenjeni u BIOPLAN-u*

Parameters & conversion factors *Parametri i faktori pretvorbe*	SCH I	SCH II	SCH III
Energy content at 0% MC, MJ/kg *Količina energija pri 0 % udjela vlage*, MJ/kg	19.5	19.0	20.0
Basic density, kg/solid m^3 *Osnovna gustoća,* kg/čvrste tvari, m^3	410	400	415
Bulk density, kg/solid m^3 *Obujamna gustoća,* kg/čvrste tvari, m^3	172.2	168.0	174.3
Solid content *Udio čvrste tvari*	0.42	0.42	0.42
Ratio loose – m^3 to solid m^3 *Odnos (m^3) rasute prema čvrstoj tvari*	2.38	2.38	2.38
Truck payload, tons *Nosivost kamiona,* t	35.0	35.0	35.0
Truck volume, m^3 *Obujam tovarnoga prostora,* m^3	130.0*	47.0**	130.0*
Round trip distance, km *Puni obilazak,* km	128	150	185
Dry matter loss rate, %/month *Stopa suhe tvari,* % /mjesečno	1.0	1.0	2.0
Interest rate, %/month *Kamatna stopa,* % /mjesečno	0.5	0.5	0.5

* m^3 loose, ** m^3 solid

* m^3 *rasuta tvar,* ** m^3 *čvrsta tvar*

Table 3 Harvesting, chipping, transport cost parameters used in BIOPLAN

Tablica 3. *Parametri troškova sječe, iveranja i prijevoza primijenjeni u BIOPLAN-u*

Parameters – *Parametri*	SCH I	SCH II	SCH III
Mechanized felling, bunching & forwarding, €/m^3 *Strojna sječa i izrada te privlačenje*, €/m^3	13.0	14.6	10.0*
Chipping, €/m^3 – *Iveranje*, €/m^3			
MC% <=35 – *Udio vlage*, <=35 %	5.8	3.8**	7.4
36=MC%<=50 – *Udio vlage,* 36 – ≤ 50 %	5.1	3.1**	6.7
MC%>50 – *Udio vlage*, >= 50 %	4.3	2.3**	5.9
Transport, €/km – Prijevoz, €/km	2.4	1.8	2.5

* It includes just forwarding – *Uključuje privlačenje forvarderom*

** Chipping at the energy plant – *Iveranje u energani*

2011; Tahvanainen and Anttila 2011). Storage costs in the model are based on the assumption that there have been costs associated with harvesting and transporting the material to roadside and that these costs have been paid for at the time of harvest. Thus, storage costs are then the interest charge on the harvesting and transport to roadside costs since the wood owner incurs a delay due to storage in being reimbursed for these. An annual interest rate of 6% was used for the analysis, as it has been suggested and used in previous biomass studies in Finland (Laitila 2006).

2.2.3 Drying curves and algorithm – *Krivulje i algoritam*

MC of biomass materials for any given month was calculated with the drying models developed by Sikanen (2012) based on heuristic fitting. The models predict daily moisture change for seven drying periods of a year based on previous empirical experiments and historical data. For whole trees and delimbed stemwood, values by Hakkila (1962) were used. As no data on the annual variation in MC for crown biomass from final fellings were found, Hakkila's (1962) values for small-sized Norway Spruce were used, but increased by 2% units. For the purpose of the analysis, and due to the lack of predictive MC models for each biomass material, drying curves were assumed to be the same for whole trees, stem wood, and logging residues (Fig. 2). In addition, dry matter loss rates per month due to storage were assumed to be 1% for whole trees and stem wood, and 2% for logging residues (Laitila 2006).

2.3 Data analysis – *Obrada podataka*

The analysis in this paper focuses primarily on the effect of MC on supply chain costs. Three aspects of the biomass supply chain and their impact on total costs and the optimal fuel supply solution were investigated with the BIOPLAN system:

⇒ Effect of different MC limits on the material arriving at the CHP plant,

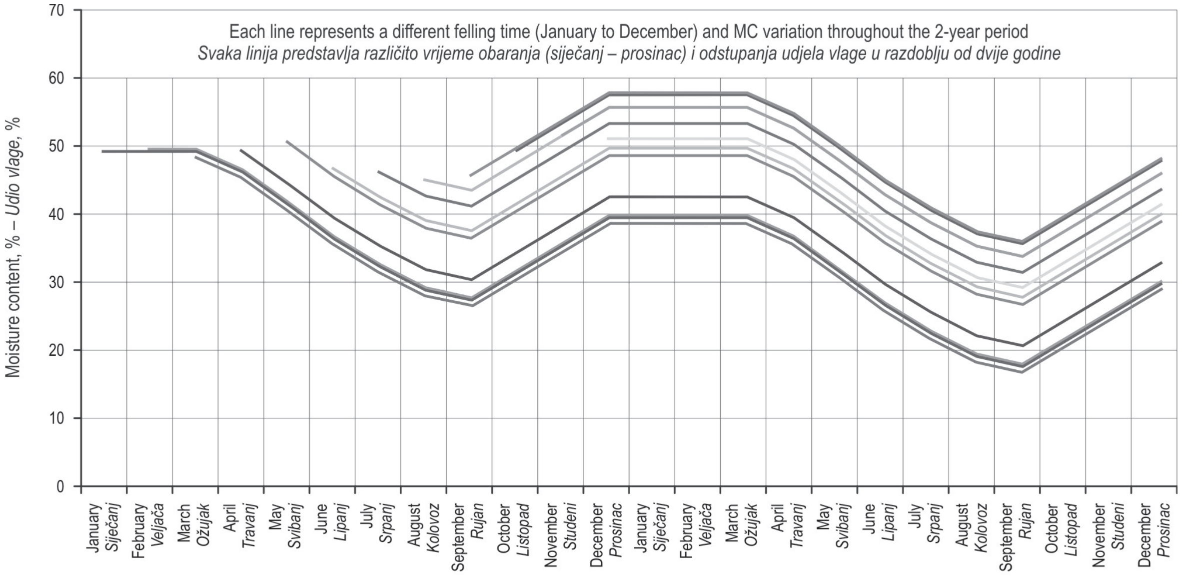


Fig. 2 Drying curves for biomass materials at different felling times

Slika 2. *Krivulje udjela vlage tijekom obaranja i skladištenja*

⇒ Effect of drying period limits on the material stored at the roadside,

⇒ Effect of more efficient drying methods.

The results of the analysis in each supply chain are presented in terms of the monthly volume of biomass material that is harvested, as well as the total supply chain costs and the costs of different operational activities (harvesting, storage, chipping, and transportation). Statistical differences of monthly volume harvested and costs by biomass material between the scenarios analyzed were checked with t-tests conducted at the p=0.05 level of significance.

2.3.1. Effect of different MC limits on total supply chain costs – *Utjecaj graničnih sadržaja vlage na ukupne troškove lanca dobave biomase*

Three scenarios were set up to investigate the effect of MC limits on supply chain costs. The first (basic) scenario did not include specific constraints to limit the MC of the biomass material (chips in supply chains I and III, and stem wood in supply chain II) arriving at the CHP plant. In the second and third scenario, we added a constraint to limit the MC of the biomass material arriving at the plant, which was set to 41–49%, and 41–43%, respectively. The latter MC range is the Joensuu CHP plant preference in their logistics operations.

2.3.2. Effect of storage time on total supply chain costs – *Utjecaj duljine skladištenja materijala na ukupne troškove lanca dobave biomase*

In BIOPLAN, the storage of any biomass material at the roadside is allowed for a period of up to 24 months (from January Year 1 to December Year 2). The optimization model determines the monthly volume that is harvested and stored at the roadside so that the supply chain costs are minimized during that period. To investigate the effect of biomass storage time at the roadside on total supply chain costs, a constraint was added to limit the number of periods (months) of storage. There was particular interest in knowing if storage for a period shorter than 12 months had a substantial effect on the biomass supply chain costs. Therefore, in addition to the unconstrained scenario (no limits on storage), two scenarios were established which constrained the storage period to a maximum of 6 periods, and a minimum of 3 periods, respectively.

2.3.3 Effect of more efficient drying methods on supply chain costs – *Utjecaj djelotvornijih načina sušenja biomase na ukupne troškove lanca dobave*

Effective drying of biomass material, including covering, is essential to decrease the MC of biomass material. MC can be reduced in a few months by 10–20% using only solar and wind power if biomass material is covered (Röser et al. 2010) To analyze the effect of covering on biomass supply chain costs, and in the absence of accurate drying curves for covered material, we established two hypothetical scenarios where the drying rates for all the biomass materials were adjusted by 10% and 15% in the autumn and winter months (October to April), assuming a lower rate of rewetting of the biomass materials when they are covered during these months. Due to the lack of information, covering costs were assumed to be € 1/m^3.

3. Results and Discussion – *Rezultati s raspravom*

3.1 Effect of different MC limits on supply chain costs – *Utjecaj graničnih sadržaja vlage na ukupne troškove lanca dobave biomase*

For the three scenarios analyzed (unconstrained, 41–49% MC, 41–43% MC), Fig. 3 shows the MC (%) curves of biomass material (chips or stem wood) delivered to the plant during year two. In the unconstrained scenario, the biomass materials present a much higher variation in MC throughout the year, especially for whole trees and logging residues. Maximum and minimum MC values were 52.3% and 41.5% for whole trees, 53.7% and 39.6% for logging residues, and 51.2% and 42.6% for stem wood. As expected, the biomass material delivered to the plant during the summer had a much lower MC than in autumn and winter. During the winter months (November to March), logging residues had a lower MC (average 48.6% MC) compared to whole trees and stem wood (average 50.3% MC), which resulted from much longer average drying periods (> 1 year) at the roadside for logging residues (7 months compared to less than 1.5 months for whole trees and stem wood).

Variation in post-storage MC for logging residues was much higher than for stem wood and whole trees (std. dev. 5.4 versus 2.8 for stem wood and 3.4 for whole trees) in the unconstrained scenario. Conversely, there was no variation for any of the biomass materials produced (whole trees and logging residues) (std. dev. = 0) when MC was constrained to 41–43%, as the MC of these materials was always at the top of the range (43%).

Fig. 4 shows the volume harvested per year by biomass material for the three scenarios analyzed. Only the mean volume differences between whole trees and logging residues harvested in the year 1 and 2 were statistically significant (p<0.05). In the unconstrained

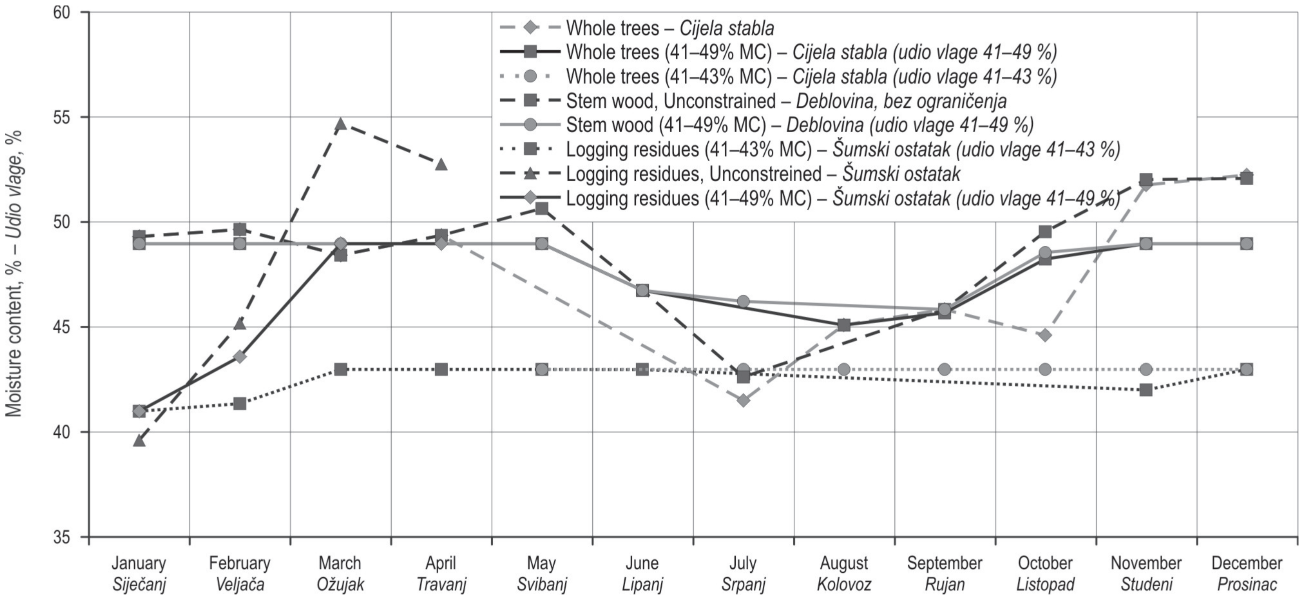


Fig. 3 Variation in post-storage MC for whole trees, stem wood, and logging residues used in the second year for energy generation in the three MC scenarios analyzed

Slika 3. *Promjene u sadržaju vlage kod cijelih stabala, debla i šumskoga ostatka pri dužem skladištenju (korištenje tek druge godine)*

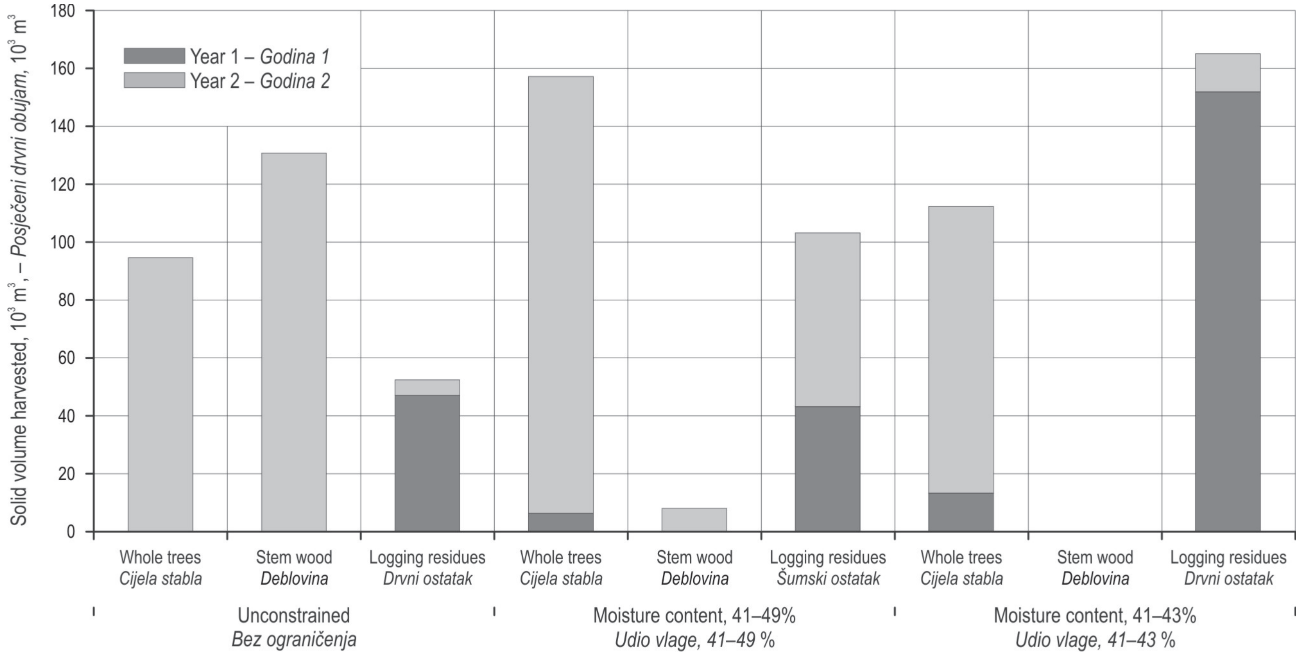


Fig. 4 Solid volume (m3) harvested for whole trees, stem wood, and logging residues in the three MC scenarios analyzed

Slika 4. *Obujam čvrste tvari za cijela stabla, debla i drvni ostatak u tri različita scenarija*

scenario, logging residues were mostly produced in the year 1 (47 118 m^3 or 100% of the total biomass material harvested in that year) and stored at the roadside for longer periods (average of 7 months) before being delivered to the plant in the year 2. This is the result of lower harvesting costs for logging residues, which allows for longer storage periods as the interest on the harvesting cost (storage cost) is reduced in comparison to whole trees and stem wood. Conversely, due to the cost structure and lower energy content of whole trees (and to a lesser extent stem wood), the optimal solution only allows for short periods of storage at the roadside, with chipping and transportation occurring just a few periods after the harvest and storage. These supply chains were used primarily in the year 2, when approximately 41% of the material harvested (94 770 m^3) corresponded to whole trees and 57% of the material harvested (130 979 m^3) corresponded to stem wood.

When MC was constrained to 41–43%, the solution precluded the harvest of stem wood and the energy demand was mostly met with logging residues harvested during the first year and whole trees harvested during the second year. Similarly, when MC was constrained to 41–49%, the volume harvested of stem wood was just marginal and accounted for less than 1% of the total volume harvested in the year 1, and about 3% of the total volume harvested in the year 2.

The volume of logging residues harvested in the year 1 was 43 170 m^3 (87% of the total volume harvested) when the MC ranged between 41–49% and 152 161 m^3 (92% of the total volume harvested) when the MC ranged between 41–43%. Whole trees was the predominant biomass material harvested in the year 2 with 151 161 m^3 (69% of the total volume harvested) when the MC ranged between 41–49% and 99 209 m^3 (88.2% of the total volume harvested) when the MC ranged between 41–43%. The predominance of logging residues and whole trees is due to their lower harvesting costs (which is the main cost component in the three supply chains) in comparison to whole trees. This reduction in harvesting costs offsets the higher chipping and transportation costs of these two biomass materials. In addition, the reduction in harvesting costs makes storage more cost effective for logging residues and whole trees, allowing for longer storage periods of these biomass materials (average of 1.5 months for whole trees and 7 months for logging residues, versus average of 1 month for stem wood).

Despite the effect of MC limits on the volume and distribution of the biomass harvested, no statistical differences were obtained in terms of supply chain costs (Fig. 5) in the three scenarios analysed ($p < 0.05$). In part, this is explained by the fact that the harvesting and extraction of biomass materials to roadside are the major supply chain cost component, which however, are not affected by moisture content. Also, in constrained scenarios, the solution tends to adjust the proportion of the materials that minimizes the supply chain costs, based on the contribution of their operational activities (harvesting, storage, chipping, and transportation) to the objective function. On a per m^3 solid basis, the total supply chain costs in the unconstrained scenario were a bit lower than those in the 41–49% MC, and the 41–43% MC constrained scenarios. This was basically due to the balanced proportion of stem wood in relation to whole trees and stem logging

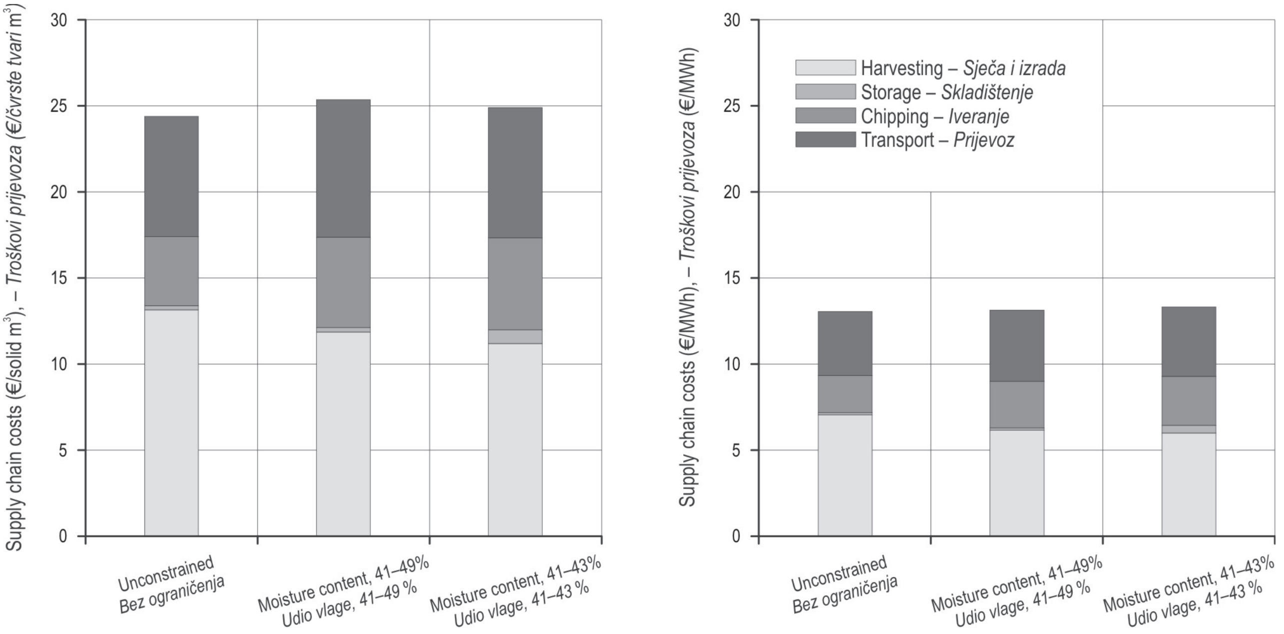


Fig. 5 Supply chain costs per solid m^3 (left) and MWh (right) by operational activity in the three MC scenarios analysed

***Slika 5**. Troškovi lanaca dobave u tri različita scenarija* residues, and the lower supply chain costs associated. Due to its high harvesting and storage costs, stem wood volume was marginal in the 41–49% MC scenario, and was nil when MC was constrained to a tight 41–43%. On a per MWh basis, there was no major difference in supply chain costs between the three scenarios, although chipping and storage costs were bigger in the 41–43% MC scenario. Total transportation costs were similar in the three supply chains. Despite the fact that transportation cost per km was cheaper for logging residues, the longer distance assumed for this supply chain offset the savings that resulted from a lower cost per km.

3.2 Effect of drying period limits on supply chain costs – *Utjecaj vremena sušenja materijala na troškove lanca dobave biomase*

Fig. 6 shows the total volume harvested in the year 1 and 2 for whole trees, stem wood, and logging residues, when the drying period was limited to a maximum of 6 and a minimum of 3 months, and compared to the unconstrained scenario. In the unconstrained scenario, stem wood and whole trees were the predominant materials, accounting for approximately 47% and 34% of the total volume harvested in the year 1 and 2, respectively. It is clear that increasing the stor-

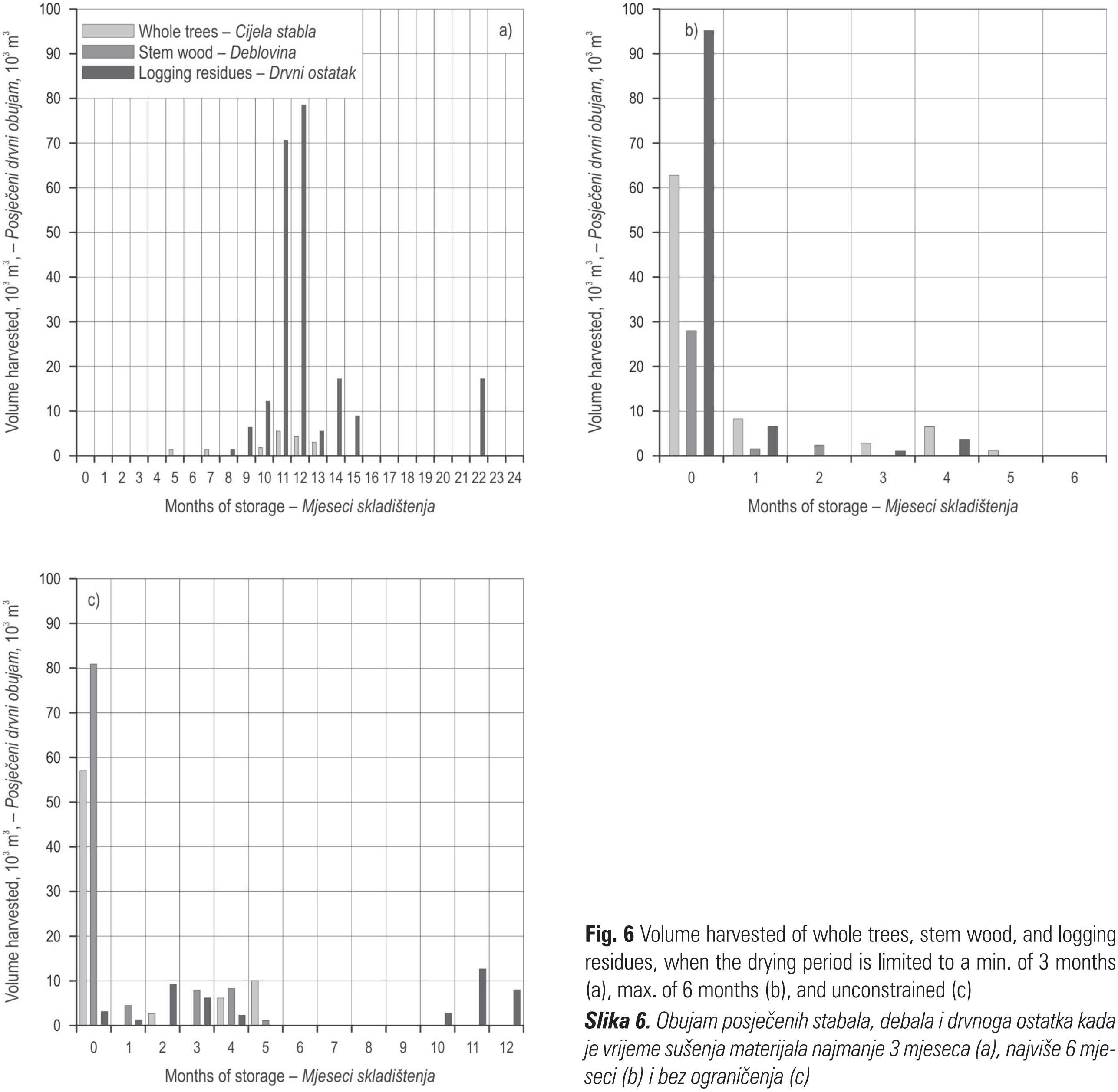


Fig. 6 Volume harvested of whole trees, stem wood, and logging residues, when the drying period is limited to a min. of 3 months (a), max. of 6 months (b), and unconstrained (c)

Slika 6. *Obujam posječenih stabala, debala i drvnoga ostatka kada je vrijeme sušenja materijala najmanje 3 mjeseca (a), najviše 6 mjeseci (b) i bez ograničenja (c)* age (drying) period to lower the MC of the biomass materials favors the production of whole trees and logging residues, since the high harvesting and storage costs of stem wood preclude the production and delivery of this material to the energy plant. For example, when storage was limited to a maximum of 6 months, whole trees and logging residues accounted for 10.2% and 89.0% of the total volume harvested, respectively. The same pattern was observed when storage was constrained to a minimum of 3 months. In this case, whole trees and logging residues accounted for 8.2% and 91.8% of the total volume harvested, respectively.

In terms of the average storage period, most of the volume of stem wood is only stored for a reduced number of periods. In the unconstrained scenario, 79% of the stem wood volume is stored for less than one month, whereas when the maximum storage period is constrained to 6 months, 90% of the volume is stored for less than one month. In the case of whole trees, shorter storage periods are obtained in the unconstrained scenario and when the storage period is constrained to a maximum of 6 periods. In these two scenarios, 100% of the volume harvested of whole trees is stored for less than 5 months, and a high proportion of this material (about 75% in each scenario) is not stored at the roadside but delivered to the plant right after the harvesting. Conversely, logging residues are stored for longer periods. In the unconstrained scenario, 52% of the volume harvested of logging residues is stored for a period between 10 and 12 months. Likewise, when the drying period is constrained to a minimum of 3 months, 100% of the volume harvested of logging residues is stored for a period longer than 8 months, with a maximum and an average storage period of 22 and 12 months, respectively. The longer storage period of logging residues is explained by the lower harvesting costs, as well as by the lower storage costs, which are calculated as the interest charge on the harvesting and transport to roadside costs.

Despite the differences in production that resulted from the constraints added to limit the storage period, no substantial differences in supply chain costs were observed across the scenarios. In comparison with the unconstrained scenario, the cost per m^3 and per MWh only increase by less than 1% when the storage period is limited to a maximum of 6 months or to a minimum of 3 months. These results indicate that the volume distribution of the biomass materials is quite sensitive to the storage period, although no major differences are obtained in terms of the supply chain costs per m^3 harvested.

3.3 Effect of more efficient drying methods on supply chain costs – *Utjecaj djelotvornijih načina sušenja biomase na troškove lanca dobave*

The positive effect of proper piling, covering, and handling methods, to lower the MC and maintain the lower MC over the winter months has been noted in several earlier studies (Ryan 2009; Anheller 2009; Röser et al. 2011). These methods provide direct financial benefits by increasing the energy content and facilitating a more efficient chipping and grinding operation. Table 4 presents the results of simulated covering on supply chain costs. When the drying rates of the materials are adjusted by 10% and 15% (less rewetting in autumn and winter months), supply chain costs increase by about € 0.43/ m^3 and € 0.81/ m^3, respectively. This rise is basically explained by the addition of covering costs as well as the higher chipping costs of whole trees (the predominant biomass material in both scenarios) that result from a lower MC. To some extent, the greater cost is also explained by the harvesting costs of whole trees and stem wood. In the unconstrained scenario, the solution includes a substantial volume of logging residues, due to their lower harvesting costs in comparison with whole trees and logging residues. Conversely, when the drying rates of the biomass materials are adjusted by 10% and 15%, the solution precludes the harvest of logging residues because of their high chipping and transportation costs, and the procurement system relies entirely on whole trees and stem wood. Although the total supply chain costs per m^3 solid increase when the MC is adjusted by 10% and 15%, the results of the analysis show that on a per MWh basis, these costs are offset by the higher energy content of whole trees and logging residues, and overall, the covering of biomass materials does not result in any substantial change in the total supply chain costs per MWh. The use of more efficient methods has an important effect on the volume of biomass materials that need to be harvested to meet the monthly demand of the energy plant. When compared to a scenario with no storage, a reduction in the volume harvested of up to 33% (from about 406 000 m^3 to 269 000 m^3) can be achieved if proper drying methods, such as covering of biomass material, are implemented before chipping and delivering the biomass materials to the energy plant.

4. Conclusions – *Zaključci*

In this study, a linear programming-based optimal decision support tool, named BIOPLAN, has been developed and implemented to assess the effect of bio-

Table 4 Costs per m^3 and MWh by operational activity for different rewetting rate scenarios

Tablica 4. *Troškovi različitih radnih aktivnosti po scenarijima*

	Unconstrained – Bez ograničenja		10% LRR*		15% LRR**	
Activity – *Radnje*	€/m^3	€/MWh	€/m^3	€/MWh	€/m^3	€/MWh
Harvesting – *Pridobivanje drva*	13.19	7.04	13.87	7.32	13.43	6.94
Storage – *Skladištenje*	0.24	0.13	0.15	0.08	0.15	0.08
Covering – *Prekrivanje*			0.35	0.18	0.35	0.18
Chipping – *Iveranje*	4.02	2.15	4.11	2.17	4.79	2.48
Transport – *Prijevoz*	6.99	3.74	6.39	3.37	6.54	3.38
Total – *Ukupno*	24.44	13.06	24.87	13.13	25.25	13.06

*10% lower rewetting rate – ** 10 % niži udio vlaženja*
15% lower rewetting rate – * 15 % niži udio vlaženja*

mass moisture content on supply chain costs. In complex supply chains, there are a number of factors associated with the production and procurement of biomass materials to energy plants that drive the solutions when using an *optimization* approach. These considerations have to be taken into account by logistics planners if fuel procurement from forests and energy production at the plant are considered simultaneously. Getting a better understanding of the tradeoffs associated with the storage of biomass materials before they are delivered to energy and heating plants is key to meet the energy demand at minimum cost. These considerations include an understanding of the effect of the length of time in storage and its positive impact on transport costs and the efficiency at the plant, as well as the negative implications such as biomass material decomposition, higher chipping and storage costs associated with the capital that is bound to the storages.

Results of this study indicate that in the majority of the scenarios assessed, whole trees and logging residues are the predominant delivered biomass material to the CHP plant. This is the result of the lower harvesting costs and the higher energy content associated with this biomass materials. The lower harvesting and storage costs of logging residues allows for longer storage periods as opposed to whole trees and stem wood which are mostly stored for short periods. In constrained scenarios (including a limit of the MC of the biomass materials delivered to the plant, and a limit of the storage period), the solution precludes the production of stem wood due to its high harvesting and storage costs and lower heating value in comparison to logging residues and whole trees. In regard to the volume of biomass materials required to meet the monthly demand of the energy plant, a reduction of up to 33% can be achieved if covering of biomass material is implemented before chipping and delivering the biomass materials to the energy plant.

Despite the limitations of our study (limited number of supply chains, same drying curves for all the biomass material, generic parameters in each supply chain), the results of the study show the importance of counting on optimal decision support tools that allows for the assessment of key fuel quality attributes and their effect on supply chain costs.

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Sažetak

Predviđanje i praćenje sadržaja vlage radi poboljšanja u logistici pridobivanja biomase

Kako bi se zadovoljila sve veća potražnja za šumskom biomasom, moraju se usavršiti pravilne tehnologije pridobivanja biomase (uključujući usitnjavanje, rukovanje i skladištenje biomase) radi proizvodnje biogoriva visoke kakvoće. Potrebno je bolje poznavanje skladištenja biomase prije nego što se ona dopremi na glavno stovarište ili u energanu kako bi se postigli viši energijski učinci uz manje troškove. To uključuje poznavanje razdoblja skladištenja biomase s *mogućim pozitivnim utjecajem na troškove prijevoza i energijsku učinkovitost u energani, te predviđanje mogućih negativnih učinaka kao što su razlaganje drvnoga materijala i viši troškovi iveranja i skladištenja nastalih zbog vezanoga kapitala u skladištima.*

Najvažnija značajka kakvoće iverja ili sirovine za proizvodnju iverja jest udio vlage (MC). Ona utječe na toplinsku vrijednost, svojstva skladištenja, troškove iveranja i prijevoza. Za procjenu utjecaja sadržaja vlage biomase na troškove lanca dobave razvijen je alat (linearno programiranje) za potporu odlučivanja koji smanjuje troškove lanca dobave, uključujući troškove pridobivanja biomase, skladištenja, iveranja i prijevoza. Pri istraživanju je korištena postojeća bioenergana u Finskoj te su proučena tri lanca dobave biomase: biomasa od cijelih stabla iz ranih proreda, deblovina iz ranih proreda i šumski ostatak iz dovršnoga sijeka. Najveći udio biomase bio je iz cijelih stabala te iz drvnoga ostatka (zbog nižih troškova pridobivanja i više energijske vrijednosti). Niži troškovi pridobivanja i skladištenja drvnoga ostatka omogućuju dulje razdoblje skladištenja, za razliku od skladištenja cijelih stabala i deblovine koji se uglavnom skladište u kraćim razdobljima. Prilikom postavljenih ograničenja u pridobivanju biomase (uključujući granične vrijednosti udjela vlage te dopuštenoga vremena skladištenja) isključuje se proizvodnja biomase iz deblovine zbog troškova pridobivanja i skladištenja te niže energijske vrijednosti. Moguće je smanjiti mjesečnu potražnju energane za biomasom za 33 % ako bi se materijal pokrivao prije samoga iveranja i prijevoza.

Unatoč ograničenjima u istraživanju (ograničen broj lanaca dobave, iste krivulje sušenja biomase, generički parametri u svakom lancu dobave) rezultati istraživanja pokazuju važnost pravoga alata za podršku odlučivanju koji omogućuje procjenu ključnih značajki te njihov utjecaj na troškove lanca dobave biomase.

Ključne riječi: udio vlage, lanac dobave biomase, razdoblje skladištenja i prijevoza, linearno programiranje, prekrivanje biomase

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