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Pre-Harvest Assessment based on LiDAR Data

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Abstract – Nacrtak

Sourcing is the first line of competitiveness of timber supply networks, identifying and locating stands to be harvested that best fit to market demands. The sourcing process is difficult because information is either only available on an aggregated level or is even unavailable, e.g. on non-industrial forest owner's land. Our study aimed to explore a LiDAR-data-based approach to improve the sourcing of stands to be harvested. We developed a spatially explicit approach, consisting of three steps: 1) harvest screening at the management unit scale or even larger, 2) location and delineation of cutting units, 3) characterization of tree attributes that are required for stand (cutting unit)-level bucking optimization.

The study resulted in the following major findings. First, a tree map represented with Voronoi cells is a useful tool to support the harvest screening process, because it is easily readable and understandable, even by operations personnel. Second, cutting unit location and delineation can easily be done on the tree map, too. Third, the estimation of stem distribution over DBH of a cutting unit may easily be extracted from the spatial tree map database, assuming that there is a deterministic relationship between tree height and DBH. However, there are still issues to be improved, such as comparison of LiDAR-based results with ground-truth, the improvement of LiDAR-based tree delineation methods, the improvement of the estimation of stems over both DBH and tree height, or a mathematical formulation and solution of cutting unit layout.

Keywords: LiDAR, tree delineation, Voronoi tessellation, harvest layout planning, pre-harvest assessment

1. Introduction – *Uvod*

Supply chain management has been the dominating concept to coordinate all activities within a supply chain network, from »the sourcing« of stands to be harvested to the production of forest products, aiming to concurrently improve value recovery and to reduce supply cost. Recent work reported how supply chain activities may be optimized from the portfolio of stands to be harvested to a set of mils to be supplied with logs with mathematical techniques (Chauhan et al. 2011). However, this type of sophisticated approach is only feasible if reliable, accurate information on the stands to be harvested is available. In many cases there is only aggregated information for the stand level, whereas information about individual trees has been missing. The situation for nonindustrial forest owners is even worse; in many cases no useful information is available, and even government programs could not motivate those owners to increase the level of harvesting (Beach et al. 2005; Hyytiäinen and Penttinen 2008).

From a systems perspective there are three macro processes that operationally perform the supply of goods and services, sourcing, making, and delivering (Scor 2010). The sourcing process aims to 1) identify, locate, select and characterize supply sources, 2) to manage supplier networks and supplier agreements, and 3) to manage supply inventory (Scor 2010). The first step, the location, selection and characterization of supply points (stands to be harvested) depends on the availability of accurate, useful information. In terms of transaction cost economics the effort of information acquisition is called search cost (Pereira 2005), consisting of the cost of acquiring the information, and the opportunity cost for the searching time.

We hypothesize that light detection and ranging (LiDAR) technology provides opportunities to improve the efficiency of sourcing stands to be harvested, primarily by increasing value recovery through improved matching of supply and demand. The present paper aims to explore the potential of LiDAR data, particularly 1) to improve screening effectiveness for cutting units at the management unit level, 2) to evaluate alternative cutting unit layouts, and 3) to acquire information for cut-block-level bucking optimization, following ideas of (Chauhan et al. 2011; Laroze and Greber 1997). The paper first presents some background information on LiDAR technology and approaches to delineate trees and stands from LiDAR data, then develops a methodology to extract and present relevant information and finally presents a case study from a region in the Eastern Swiss Alps.

2. Background – *Pozadina istraživanja*

2.1 LiDAR Technology – *Tehnologija LiDAR*

Light detection and ranging LiDAR is a remote sensing technology that creates a geo-referenced, 3D point cloud, representing a surface »sensed« by a laser sensor (Flood 2001). It is a »sister technology« of RADAR, radio wave detection and ranging, and was therefore also called LADAR, laser detection and ranging. Three functions have to be performed to yield geo-referenced coordinates of a surface, 1) ranging, providing the distance between the sensor and points of an object; 2) positioning, providing the coordinates of the sensor in space and time; 3) orientation, capturing the direction of the laser sensor at the time of laser emission. The first LiDAR systems were ground borne and used to detect scattering layers in the upper atmosphere (Fiocco and Smullin 1963). It was only during the 1980s when NASA developed experimental airborne LiDAR systems (Krabill et al. 1984), triggered by the availability of highly accurate global positioning system GPS, but it took about 10 years more until LiDAR technology started to becoming widely used, when commercial systems became available (Flood 2001).

The application of airborne laser systems for forestry started by the end of the 1990s with the determination of terrain elevations, the estimation of stand height and volume, and the location and segmentation of individual trees (Hyyppä et al. 2004). At the same time papers providing a comprehensive overview on the technology and on the physical principles (Baltsavias 1999; Wehr and Lohr 1999) appeared. A review done in 2004 (Hyyppä et al. 2004) came to the conclusion that there is a relatively good understanding of extraction of digital terrain models DTMs and Crown Heights models CHMs, but that there are open issues such as the use of full waveform data, the complementary use of airborne and terrestrial laser scanning, and improved techniques to process 3D- point clouds. A more recent review (Mallet and Bretar 2009) presents the state-of-the-art of full waveform LiDAR technology. It provides more accurate range detection, particularly over complex surfaces, but also offers an opportunity to extract additional parameters, such as dead branch crown base of trees, or the general characterization of the vertical structure of forest stands. However, we do not yet make use of the range of information of full-waveform data, particularly the profiles of intensity and amplitude.

2.2 Extraction of Tree and Stand Attributes *Izdvajanje stabala i opis sastojine*

Advances in processing techniques for LiDAR data offer the possibility to identify the location and the height of individual trees and of their crown geometry. The first processing step usually consists of surface smoothing, using filtering techniques, such as Gaussian Kernel filtering (Hyyppa et al. 2001; Morsdorf et al. 2004), followed by surface modeling techniques. Nine research groups compared the competitiveness of their tree extracting approaches on a joint data set (Kaartinen et al. 2008). Identification accuracy compared with ground truth was between 25% and 90%, and the so-called TopHat algorithm, a method of mathematical morphology, performed best. The TopHat algorithm is implemented in mathematical software tools, such as Matlab and Mathematica, and one can assume that other methods of mathematical morphology perform comparably or even better. Former TopHat studies came to the conclusion that the algorithm works well if tree crowns are relatively large and widely dispersed, but that its performance depends on the size of the morphological element (a circle) and the predominant tree crown size (Anderson et al. 2001). Another finding of the (Kaartinen et al. 2008) study was that an increase of laser pulse density from two points per square meter to eight points per square meter improved identification accuracy significantly. A recent study (Vauhkonen et al. 2012) compared tree extraction algorithms, however without investigating the performance of the TopHat algorithm, concluded that forest structure, particularly tree density and tree clustering affects algorithmic performance considerably.

Traditionally, stand delineation is the process of experts interpreting aerial photographs, following best practice rules. However, those rules are not logical at all, but strongly depend on the skills of the analyst, the local nature of site conditions, and traditions of the local forest service (Sullivan 2008). There has been considerable attempt to automate the stand delineation process by segmenting digital imagery. Image segmentation is a process that divides an image into spatially disjoint, homogenous areas (Mustonen et al. 2008). The development of automatic or semi-automatic stand segmentation methods is still an emerging field that has its roots – to our knowledge – in the work of the remote-sensing Institute of the University of Freiburg, Germany, in 2003 (Diedershagen et al. 2004; Diedershagen et al. 2003; Weinacker et al. 2004). A recent study from the same Institute reviews the state-of-the-art on stand segmentation (Koch et al. 2009). Available approaches are based on a normalized digital surface model that is converted into an image, which is analyzed with image segmentation techniques to delineate homogeneous areas. A similar procedure was used in Finland, confirming that image segmentation techniques based on crown height models perform better than the same techniques applied to spectral image data (Mustonen et al. 2008). However, there is still a strong need to improve stand segmentation methods, because the question how the abstraction process of aerial photograph interpreters is working, has not been conceded so far, and we still lack a consistent approach that produces comprehensible stand delineation results.

Mountain forests, which are expected to provide ecosystem services, such as protection, have to be maintained in artificial steady-state equilibrium. Silvicultural interventions are aimed at triggering stand regeneration by imitating the so-called »gap dynamics«, which is a small-scale disturbance pattern of the forest canopy (Mccarthy 2001). As a consequence, there is a need to characterize forest gaps spatially explicit. To our knowledge, there are only few studies on gap identification (Vepakomma et al. 2008; Zhang 2008). A study on gap detection and mangrove forests resulted in the finding that morphological filtering clearly outperformed the so-called »height method« (Zhang 2008). Methods of mathematical morphology provide a high potential for the identification and characterization of regeneration gaps for uneven-aged management regimes and could be used for silvicultural priority assessment and protection service forests, as described by (Frehner et al. 2005).

3. Study Object and Methods – *Objekt i metode istraživanja*

3.1 Study Object – *Objekt istraživanja*

The study object is located in eastern Switzerland and bounded by the following UTM (zone 32T) coordinates: west/south (563’500, 5’191’545); north/east (564’655, 5’192’455). The forests are located on a North-faced steep slope at an altitude of 1300 to 1700 m above sea level. They belong to the subalpine vegetation zone that mainly consists of Norway spruce (*Picea abies* L. / Karst/). The rationale for the choice of the study object was threefold. First, it only consists of one tree species. Second, there is considerable amount of structural variability, both horizontally and vertically. And third, high-resolution LiDAR data were available.

3.2 LiDAR data – *Podaci dobiveni iz LiDAR-ovih snimaka*

Airborne laser scanning was performed between September 11 and 15, 2010, with a Trimble Harrier 68 scanner (TRIMBLE, online). The Harrier 68 scanner is an advanced, pulsed laser corridor mapping system that generates extremely dense point clouds in combination with geo-referenced ortho images. It has a built-in full waveform digitization device, which enables the extraction of comprehensive vertical information from the acquired signals. The average flight height was about 700 m above ground, and the emitted laser point density was about four points per square meter. The laser scanner service provider did the data pre-processing, particularly the transformation from WGS 84 into the Swiss coordinate system and the extraction of the following data models:

- ⇒ DSM-FE (digital surface model first echo), providing the surface model including canopy, buildings, etc.,
- ⇒ DSM-LE (digital surface model last echo), providing the terrain surface, however with »holes« for which no last echo response is available,
- ⇒ DTM (digital terrain model), providing the terrain surface without canopy, buildings, etc.,
- ⇒ FDTM (filled digital terrain model), providing terrain surface, including »holes« filled by interpolation.

3.3 Workflow of and Tools for LiDAR processing *Tijek rada i korišteni alati za analizu LiDAR-ovih snimaka*

Post-processing of LiDAR data aims at extracting information that is useful for a specific type of problem. However, post-processing of LiDAR data to extract stand and tree information is a relatively new research topic. As a consequence, there is not »the one best way« for post processing. Our approach consists of the following analysis steps: 1) extraction of a crown height model CHM, 2) identification of canopy gaps, 3) extraction of tree attributes, and 4) the assessment of the harvesting corridor. Table 1 illustrates the workflow along the four main steps by allocating procedures and software tools. We used ArcGIS 10 and

Table 1 Pre-harvest assessment workflow. Toolboxes refer to ArcGIS 10 and to Matlab R2010a software
Tablica 1. *Tijek izrade plana sječe s pripadajućim opisom pojedinog postupka i korištenim alatima*

Step – *Korak*	Procedure – *Postupak*	Toolbox – *Alat*
Extract crown height model CHM *Izrada digitalnoga modela visine krošanja*	Import digital terrain model DTM and digital surface model DSM *Unos digitalnoga modela terena i digitalnoga modela površine*	ArcGIS
	Subtract DTM from DSM to yield canopy height model CHM *Preklapanje digitalnih modela kako bi se dobio digitalni model visine krošanja*	ArcGIS Raster Calculator
	Smooth CHM *Korekcija digitalnoga modela krošanja*	ArcGIS Focal Statistics (Gaussian Kernel Filter)
Identification of canopy gaps *Obilježavanje progala*	With CHM identify canopy gaps *Pomoću digitalnoga modela krošanja prepoznati površinu progala*	Matlab image toolbox, series of morphological opening and closing operations
Extract tree attributes *Prikupljanje podataka o stablima*	With CHM, identify tree locations (local maxima) and assign tree heights h^t *Odrediti položaj stabla u sastojini pomoću digitalnoga modela krošanja te svakomu stablu dodijeliti odgovarajuću visinu*	ArcGIS Focal Statistics, Raster Calculator
	With tree height h^t, estimate DBH, see equation (2) *Pomoću visine stabla izračunati prsni promjer (jednadžba 2)*	ArcGIS Raster Calculator
	With h^t, estimate tree volume V^t, see equation (1) *Pomoću visine stabla izračunati obujam stabla (jednadžba 1)*	ArcGIS Raster Calculator
	With h^t, DBH and V^t create GIS tree point layer *Pomoću visine, prsnoga promjera i obujma napraviti bazu stabala u GIS-u*	ArcGIS MultiValue to Point
	With tree point layer create tree Voronoi cells *Pomoću GIS-ove baze napraviti Voronoiev dijagram*	MatLab, Voronoi function
Evaluate cable corridor *Ocjena žične linije*	Define cable road – *Odrediti žičnu liniju* Establish buffer for cable road with maximum lateral yarding distance *Postaviti buffer s najvećom postranom udaljenosti privlačenja*	ArcGIS line object Arc GIS buffer function
	With tree point layer, select trees that are located within the buffer zone *U GIS-ovoj bazi označiti stabla koja se nalaze unutar površine žične linije*	Arc GIS spatial join function
	With selected trees, calculate DBH distribution Izračunati prsni promjer odabranih stabala	Export attribute file to EXCEL

Matlab software to implement the series of procedures that are required to perform the four main steps.

The first step, the extraction of the canopy height model CHM, is rather well understood (Hyyppä et al. 2004), it is the result of subtracting the digital terrain model DTM from the digital surface model, the DSM, and of interpolating empty grid nodes (Solberg et al. 2006).

The second step, identification of canopy gaps, is essential for Norway spruce stands in higher elevations because trees are not distributed uniformly, but are clustered. Natural regeneration initiates in canopy gaps, assuming that there is enough light and heat getting on the ground to enable the growth of seedlings. We implemented an algorithm proposed by (Zhang 2008), which is based on methods of mathematical morphology (alternating sequential filter), and which proved to be more flexible than other methods. Subtracting the gap area from the forest area results in the area in which trees may occur.

The third step consists of identification of tree location, estimation of tree height and tree volume. Former studies reported that the crown surface model needs to be smoothed (Hyyppä et al. 2004; Solberg et al. 2006) to get close-to-reality results. Whereas mild smoothing produces a high share of »true trees«, but also many »false trees«, tough smoothing results in underestimating of »true trees« (Solberg et al. 2006). Therefore, the best setting for smoothing is usually identified by trial and error. We used a 3x3 Gaussian Kernel filter, the smoothness effect of which is slightly larger than the one of the filter proposed by (Hyyppa et al. 2001;

Morsdorf et al. 2004). Locations of trees correspond to local maxima on the smoothed canopy height model CHM. A local maximum is a node that has larger height values than its eight grid neighbors (Solberg et al. 2006), and the cell centroid is an estimate for the location coordinates of that tree. Tree segmentation aims at defining a segment around each tree location to represent the crown footprint. A region growing algorithm (Solberg et al. 2006) proved to yield crown footprints with reasonable accuracy. For pre-harvest assessment we are interested in the base area that a single tree occupies. Computational geometry provides a method called Voronoi partitioning, a procedure to »partition the plane with points into convex polygons such that each polygon contains exactly one generating point and every point in a given polygon is closer to its generating point than to any other« (Weisstein online). Voronoi segmentation was used to investigate the influence of available plant space on yield (Mead 1966), and for spatially explicit stand modeling (Courne et al. 2009). Based on tree location points, and excluding canopy gaps, we created Voronoi cells for individual trees, which results in a tree map for a specific area. The advantage of such a map is that trees may easily be allocated to harvesting units or may be clustered into stands.

The fourth step of the analysis consists of the pre-harvest assessment of a specific cutting unit. A cable corridor is the simplest geometric shape of a cutting unit, consisting of a rectangle with the length of the cable road and the width equaling two times the maximum lateral yarding distance. Once this shape is defined, a spatial query such as »select tree locations that are located within the cable corridor« yields a tree map with Voronoi cells, the total area of which equals the harvest area. The estimation of the harvest volume and the volume distribution over DBH may be done on the selected tree subset.

3.4 Tree attribute estimation – *Procjena značajki stabala*

The traditional procedure measures DBH in the field, and then estimates both tree volume and height with empirical relationships, characterized with volume or height functions, respectively. Whereas DBH is the parameter that can easily be measured by ground surveying, height is the tree parameter that can be estimated most accurately from LiDAR data. Therefore, there is a need to have a volume estimation procedure with tree height as the main parameter. The Swiss National Forest Inventory SNFI (Brändli 2010) is based on permanent plots where information on DBH and tree height is gathered for a subset of all sample trees. We used SNFI tree data of the plots located in the valley of the test area, consisting of 756 tree data records, 135 of which with DBH and tree height measured in the field, and with tree volume estimated with SNFI volume functions. Our volume modeling approach followed the philosophy described by (Hoffmann 1982), using an exponential function with the natural logarithm of height and its forth power as independent variables [1].

$$V_t = e^{a+b\cdot\ln(h_t)+c\cdot\ln^4(h_t)} \cdot e^{\frac{\sigma^2}{2}} \tag{1}$$

V_t represents tree volume in cubic meters, h_t tree height in meters, extracted from the LiDAR data, whereas a, b, c and σ are model parameters. The second term of (1), $e^{\frac{\sigma^2}{2}}$, is s factor to correct for the bias resulting from logarithmic transformation, see (Beauchamp and Olson 1973). Regression analysis yielded the following parameter estimates: $a = -9.85$; $b = 3.51$; $c = -0.0085$; $\sigma^2 = 0.29$. DBH estimation as function of tree height is based on a height prediction formula (Ye 1995), which was solved for tree height, resulting in (2).

$$DBH = 76.9 - 0.7 \cdot \sqrt{11798 - 284.7 \cdot h_t} \tag{2}$$

The estimation of tree volume and DBH is deterministic, neglecting the residual variation of about 30% for (1).

4. Results and Discussion – *Rezultati i rasprava*

Our case study aims at exploring a pre-harvest assessment methodology based on LiDAR data and at assessing its feasibility and utility. The first step of harvest planning consists of screening forest areas for possible cutting units that fulfill two basic requirements: 1) there is a silvicultural requirement for an intervention, and 2) the possible log mix fits as close as possible to market demand. The second step consists of laying out cutting units that are operationally feasible, economically efficient, and environmentally sound. The third and final step is to estimate the total harvest volume, the distribution of volume over DBH, and the possible distribution of log classes over small length diameter and length that could be produced from the standing trees. Below, we will illustrate those three steps for our study area.

4.1 Tree Location and Segmentation – *Položaj i razvrstavanje stabala*

Traditional harvest screening is based on stand maps, aerial photographs and local knowledge of the forest guards and officers. Stand maps provide aggre-

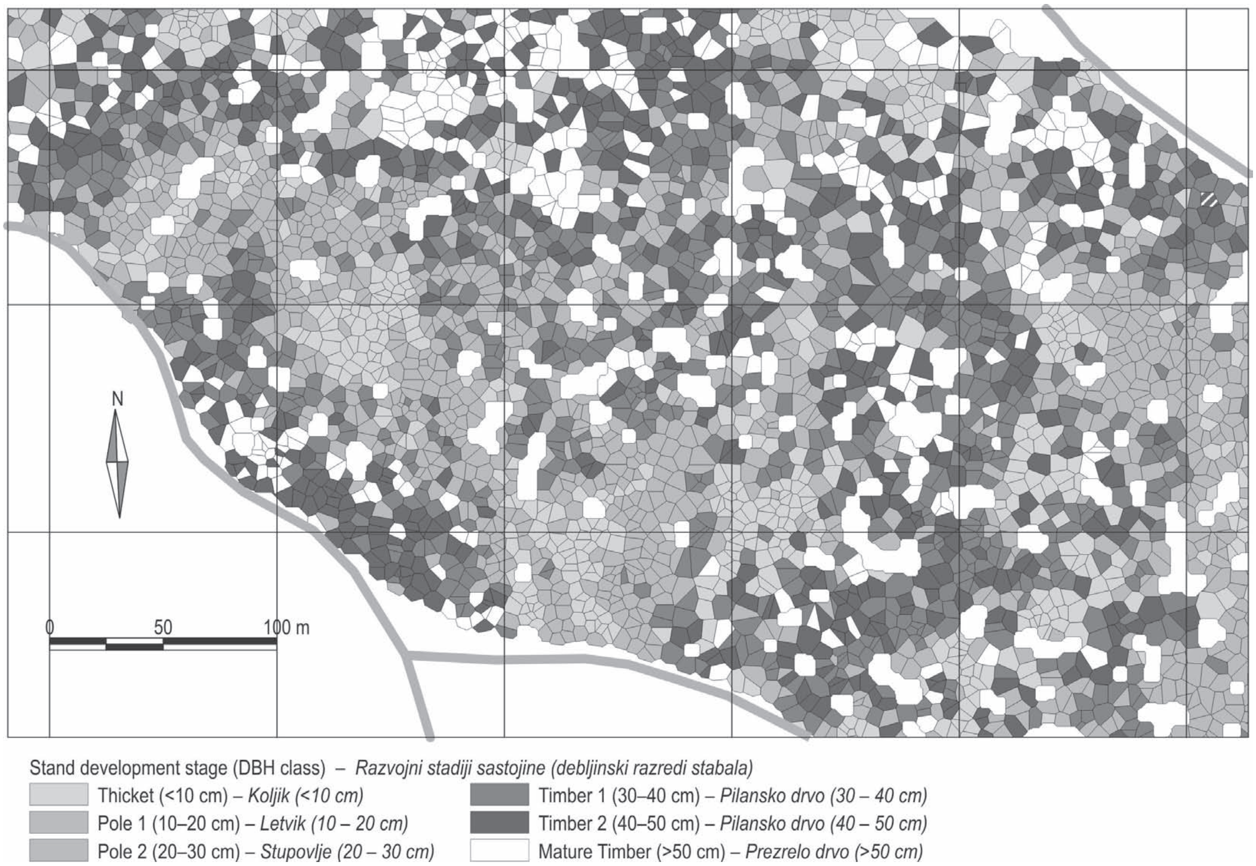

Fig. 1 Tree Map characterized with Voronoi cells. Each cell represents a single tree classified into thicket, pole, timber and mature timber development stages. White polygons are gaps. Harvest screening yields areas for wood harvesting (timber 1, timber 2, mature timber stages)

Slika 1. *Karta stabala prikazana pomoću Voronoievih ćelija. Svaka ćelija predstavlja pojedinačno stablo razvrstano u koljik, stupovlje, pilansko drvo i prezrelo drvo. Bijeli poligoni označuju progale. Za sječu je predviđeno pilansko i prezrelo drvo*

gated information that is in many cases far too general for pre-harvest assessment. We hypothesize that the tree map (Fig. 1) is the type of information that is best supporting the screening for cutting units process. Whereas age class of stands is an important planning variable for even-aged forest management, it is usually not known for uneven-aged forests. Therefore, stand development stages are used, which may be defined in terms of the dominant tree height, e.g. the average height of the 100 most dominant trees per hectare. Fig. 1 illustrates a tree map extracted from LiDAR data with Voronoi cells for each tree and each tree classified according to the development stage. The development of the thicket stage may be manipulated by silvicultural tending operations, whereas development at the pole stage can be controlled by pre-commercial thinning. Harvesting operations for wood production occur at the timber development stages that are presented in Fig. 2 with three classes: timber 1, timber 2 and mature timber. A visual assessment of

Table 2 Characteristic Tree Attributes for the management unit. The management unit, part of which is shown in Fig. 1, consists of 22.1 ha stocked forest area. Results for DBH > 12 cm

Tablica 2. *Značajke stabala u istraživanoj gospodarskoj jedinici obrasle površine 22,1 ha (slika 1). Prikazani su rezultati za stabla prsnoga promjera > 12 cm*

Attribute *Značajke stabla*	Mean *Arit. sred.*	Min *Min.*	Max *Maks.*	Std. Dev. *St. dev.*
Tree height, m *Visina stabla,* m	28.3	11.4	51.9	7.0
DBH, cm *Prsni promjer,* cm	36	12	75	13
Tree volume, m^3 *Obujam stabla,* m^3	2.7	0.2	5.5	1.3
Voronoi cell area, m^2 *Površina Voronoieve ćelije,* m^2	40	2	140	17

the tree map yields areas in which the timber development stage is predominant, those areas are candidates areas for cut block layout.

It is not possible to identify all trees in a specific area (Vauhkonen et al. 2012), but dominant trees are located in the top canopy layer, in which tree identification seems to work quite accurately. Compared to previous approaches based on stand maps, the increase in information quality and accuracy is considerable and the error has to be accepted. Based on individual tree data it is possible to produce additional maps, providing information on volume density distribution or on stand density.

4.2 Tree Attribute Extraction – *Izdvajanje značajki stabala*

We applied our screening approach to a management unit, consisting of 22.1 ha stocked forest area and a total standing volume of about 12,500 m³, corresponding to 565 $m^3 \cdot ha^{-1}$. Table 2 presents characteristic values for tree height, DBH, tree volume and Voronoi cell area. The figures illustrate that the management unit is characterized by considerable structural variability, covering tree height ranges between 11 m and 52 m, or tree volume ranges between 0.2 and 5.5 m³. About 80% of the standing volume consists of trees with a volume higher than 2.5 m³. Assuming that the volume will be harvested with a cable yarding system, the dominance of large-diameter trees will require a yarder with a load capacity higher than 25 kN.

Tabular information (Table 2) has been used to characterize management units and forest stands. However, harvest unit layout is a spatial decision, resulting in the delineation of a cutting unit. This location decision has a big impact on operational efficiency, because the delineation fixes cutting unit characteristics such as 1) the total harvest volume, 2) distribution of trees over tree volume, and 3) harvesting intensity. Harvesting intensity is an important characteristic for cable yarding with considerable amount of set up and dismantling cost, which is usually measured in cubic meters per unit length of the cable road. The higher the volume per set up, the lower the harvesting cost is.

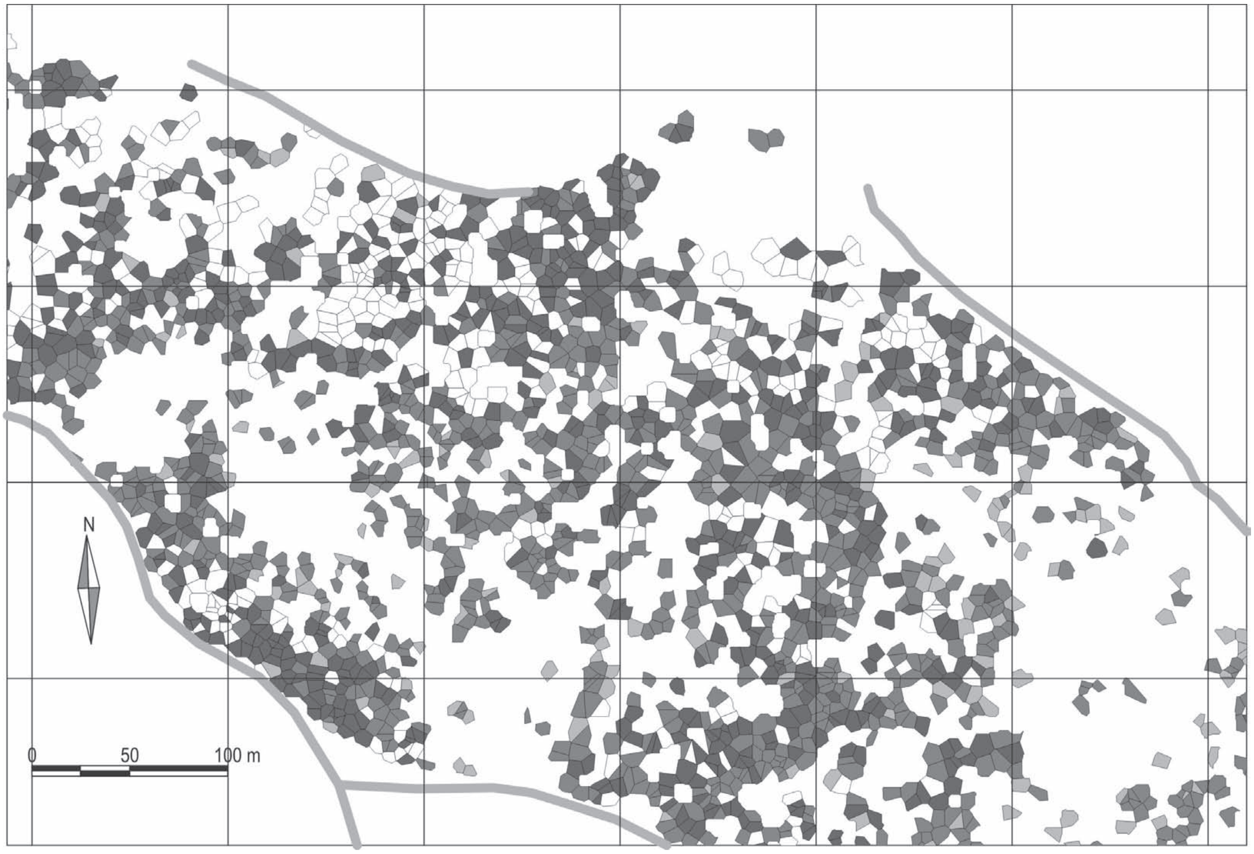

Fig. 2 Location of mature trees with a volume higher than 2.5 m³. The map is supporting harvest screening and localizing possible cutting units

Slika 2. *Karta položaja prezrelih stabala, obujma > 2,5 m³. Karta pomaže pri planiranju položaja mogućih sječina*

Spatial information (Fig. 2) on the location of mature trees is useful to identify the location of harvest units that yield high timber volume. It has been well-documented that mountain forests in the Swiss Alps are over aged and should be regenerated to continuously provide protection services (Frehner et al. 2005). »Mature tree maps« are a useful tool to identify the hotspots for a regeneration requirement for regional areas.

4.3 Pre-Harvest Assessment of a Cutting Unit
Procjena sječnih jedinica

We located and delineated a cutting unit – often called harvest layout, consisting of a cable corridor between two forest roads (Fig. 3), aiming to access two mature timber clusters, one located at the northern, and the other located at the southern road. The length of the cable road is about 260 m between head spar and tail spar. Assuming a maximum lateral yarding distance of 25 m, the cable corridor has a total area of about 1.3 ha, of which about 1.0 ha consists of stocked forest. The cable corridor is the simplest geometric shape of the cutting unit, created by defining the cable road as a line object in a GIS system and by defining a buffer of 25 m around the line object (Fig. 3). Trees located within the cutting unit are selected with a spatial query, such as »select tree locations that are located within the cutting unit area«, resulting in a cutting unit tree map (Fig. 3, right). Our cable corridor accesses about 350 trees with the total volume of 985 m^3, out of which 865 m^3 (88%) are from trees with tree volume higher than 2.5 m^3. The average standing volume of more than 800 m^3 per hectare is extremely high, and even seems to be wrong for people that are not familiar with the local conditions. However, it is well documented that Switzerland has the highest average standing volume per hectare in Europe (Brändli 2010)

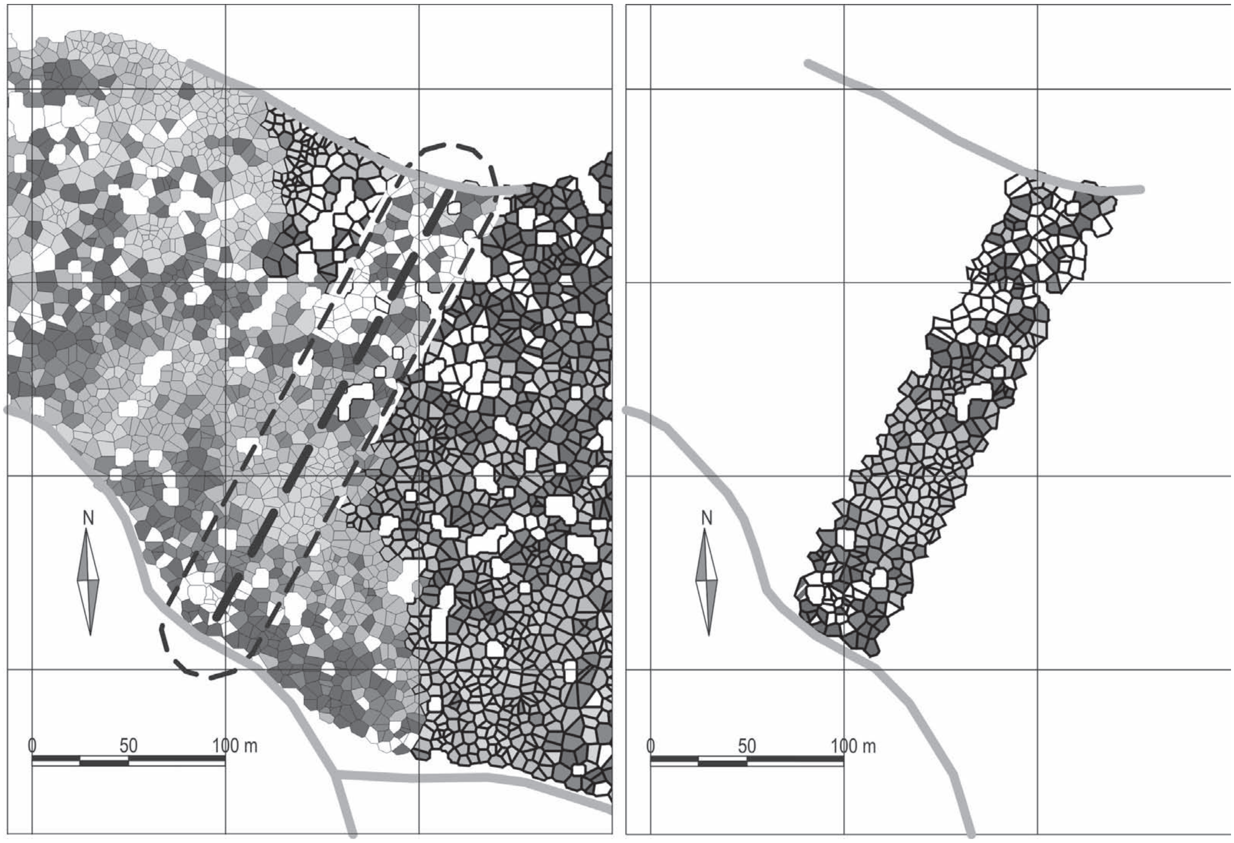

Fig. 3 Cutting Unit Layout (cable corridor). A cable corridor is the simplest geometric shape of a cutting unit, consisting of a rectangle with the length of the cable road and the width equaling twice the maximum lateral yarding distance (left). The potential harvesting volume can be estimated with a spatial query such as »select tree locations that are located within the cable corridor«, yielding a map with selected trees (right). Grid spacing: 100 m

Slika 3. *Odabrana žična linija (sječna linija). Žična je linija predstavljena najjednostavnijim geometrijskim oblikom, s dužinom užeta i dvostrukom udaljenošću postranoga privlačenja (slika lijevo). Moguće užito drvo može se procijeniti vrlo jednostavnom naredbom »označiti stabla koja se nalaze na području žične linije« (slika desno)*

Table 3 Characteristic Tree Attributes for a cable corridor. The cutting unit, shown in Fig. 3, consists of 1.0 ha of stocked forest area. Results for DBH > 12 cm

Tablica 3. *Značajke stabala na žičnoj liniji obrasle površine 1 ha (slika 3). Prikazani su rezultati za stabla prsnoga promjera > 12 cm*

Attribute *Značajke stabla*	Mean *Arit. sred.*	Min *Min.*	Max *Maks.*	Std. Dev. *St. dev.*
Tree height, m *Visina stabla,* m	31.5	11.6	46.2	8.6
DBH, cm *Prsni promjer stabla,* cm	36	12	75	17
Tree volume, m^3 *Obujam stabla,* m^3	3.4	0.2	5.5	1.6
Voronoi cell area, m^2 *Površina Voronoieve ćelije,* m^2	35	6	81	16

with local maxima up to 1000 m^3 per hectare. This is a result of a systematic underuse during the last five decades, resulting in over mature, over aged stands, particularly in mountain areas (Ott 1973).

The main purpose of pre-harvest assessment is to locate possible cutting units and to assess volume, quality and value of the standing resource. With the possible layout of Fig. 3, the standard resource is characterized with attributes such as tree height, DBH, and tree volume (Table 3). The average tree volume within the cutting unit is 3.4 m^3, covering a range between 0.2 m^3 and 5.5 m^3.

The value of the timber depends on how stems are converted into logs, which is realized by so-called cutting unit or stand level bucking decisions. The supply chain management paradigm aims to further improve the match between supply and demand and to optimize bucking operations before harvesting is carried out in the field (Chauhan et al. 2011). However, related optimization procedures only produce useful results if stand characteristics are captured at the minimum level of accuracy. The available optimization approaches of cutting unit level bucking have usually been using the following parameters: number of stems per diameter class, a set of bucking patterns for each diameter class, and market revenue for each bucking pattern per diameter class (Laroze and Greber 1997).

Fig. 4 presents the distribution of the number of stems over DBH for the cable corridor, assuming that there is a deterministic relationship between DBH and tree height. The stem distribution over DBH shows a large variability in tree size. Whereas only about 1% of the total volume are classified as small diameter timber (DBH < 20 cm), close to 60% of the total volume belong to large diameter timber (DBH > 50 cm), which is especially challenging for harvesting and processing. Up to now, similar results could only be obtained by doing a full-scale field survey, often in parallel with tree marking, measuring the DBH of each tree to be harvested and calculating tree volume with a tariff function. Full-scale field surveys, also called »100% timber cruising« (Bell and Dilworth 1997), are labor intensive and extremely costly, so that they are rarely applied anymore. Instead, sampling schemes have been a dominant approach, having the limitation that only an estimate of the real stem distribution over DBH is available.

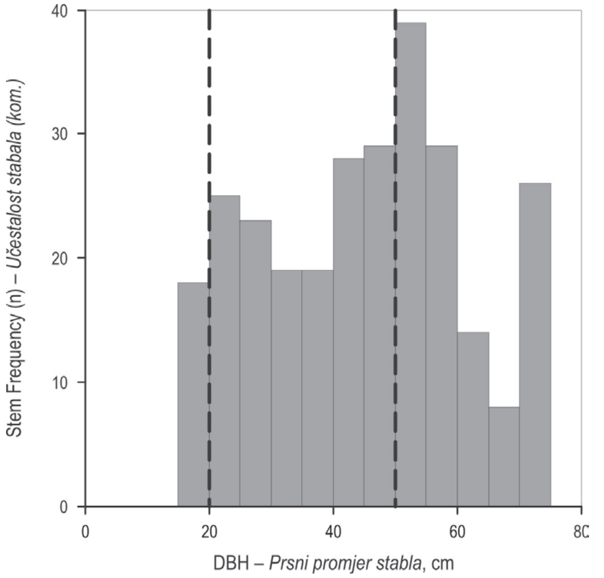

Fig. 4 Stem distribution over DBH for a cable corridor. The cutting unit, shown in Fig. 3, consists of 1.0 ha of stocked forest area. Results for DBH > 12 cm. DBH classes < 0.12 m refer to small diameter trees, >0.50 cm to large diameter trees

Slika 4. *Raspodjela stabala po prsnom promjeru na žičnoj liniji obrasle površine 1 ha (slika 3). Prikazani su rezultati za stabla prsnoga promjera > 12 cm*

5. Conclusions – *Zaključci*

Our study aimed to explore a LiDAR-data-based approach to improve the sourcing of stands to be harvested as a set of supply points for timber supply networks. We developed a spatially explicit approach, consisting of three steps: 1) harvest screening at the management unit scale or even larger, 2) location and delineation of cutting units, and 3) characterization of tree attributes required for the optimization of stand (cutting unit)-level bucking.

Our study resulted in the following major findings. First, a tree map represented with Voronoi cells is a useful tool to support the harvest screening process, because it is easily readable and understandable, even by operations personnel. Second, cutting unit location and delineation can easily be done on the tree map, too. This is particularly useful for cable yarding operations, where the layout of a cable road is always determining the delineation of a cutting unit, and where a cutting unit is never equivalent to a single stand. Third, the estimation of stem distribution over DBH of the cutting unit may easily be extracted from the spatial tree map database, assuming that there is a deterministic relationship between tree height and DBH. A tree map with Voronoi delineation improves the spatial information on timber resources tremendously, compared to best practices, which are based on stand maps, for which only aggregated information is available. Additionally, it presents the spatial variability pattern of tree size and volume, which is useful for harvest planning, as well as for silvicultural assessment.

Large scale application of our approach would have significant impacts on different supply chain actors. Processing industry would have information where timber resources are located, even on the land of non-industrial forest owners or on public land, where the forest service owns useful information but does not make it accessible to interested supply chain actors. Harvesting managers and harvesting contractors would be able to locate and delineate cutting units so that both operational efficiency and value recovery could be optimized. However, LIDAR data acquisition is still quite expensive, and cost is a major constraint to the introduction and use of the present approach. Whereas the cost of DGPS and of LIDAR sensors have been dropping (Flood 2001), operation of the carrier aircraft (helicopter, fixed-wing airplane) is still expensive. Unmanned aerial vehicles, UAVs, are a next step of development, which will reduce the cost significantly. The carrier platforms – e.g. octocopter (Wallace et al. 2012), helicopter (Yi et al. 2011) – are still in a pre-commercial state of development. Costs are expected to drop from about 45 $\$\cdot km^{-2}$ to about 5 $\$\cdot km^{-2}$ (Johnson 2006).

There are still some issues that have to be improved. The smoothing mechanism of the canopy height model CHM is the critical first link for all type of consecutive analysis. Therefore, further research on tree delineation is still required. Methods of mathematical morphology, eventually combined with well-documented approaches (Vauhkonen et al. 2012), such as Gaussian Kernel filtering, provide potential for improvement. Another important issue is to compare LiDAR-based results with ground-truth, which however requires considerable efforts and costs, see e.g. (Solberg et al. 2006). A further line of future research should try to improve the characterization of stem distribution over both DBH and tree height. Whereas tree height may be extracted with considerable accuracy from LiDAR data, DBH has to be estimated indirectly. Our approach used a deterministic relationship between tree height and DBH, whereas DBH varies for equal tree heights due to crown surface variation. And finally, mathematical identification of optimal or at least near-optimal cutting unit location and delineation could further improve operational efficiency and value recovery.

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Sažetak

Planiranje pridobivanja drva na osnovi LiDAR-ovih snimaka

Prikupljanje je podataka prvi korak razvoja konkurentnosti u procesu pridobivanja drva te određivanje sastojina za sječu koje najbolje odgovaraju potrebama tržišta. Ono je težak postupak jer su informacije ili vrlo općenite ili čak nedostupne, kao što je to u slučaju šuma privatnih šumovlasnika. Cilj je ovoga rada bio istražiti mogućnost primjene LiDAR-ovih snimaka za unapređenje prikupljanja podataka o sastojinama koje će se sjeći. Razvijen je izrazito prostorni pristup, koji se sastoji od triju koraka:

⇒ *planiranje radova pridobivanja drva na razini odjela/odsjeka ili čak na većim površinama (revir ili gospodarska jedinica),*

⇒ *određivanje položaja i prepoznavanje sječnih jedinica (odjel/odsjek),*

⇒ *opis značajki stabala koje su potrebne za optimiziranje sortimentne strukture sastojine.*

Na temelju rezultata istraživanja doneseni su sljedeći zaključci. Karta stabala, predstavljena Voronoievim dijagramom, koristan je alat za planiranje pridobivanja drva jer je lako čitljiva i razumljiva u operativnoj primjeni. Nadalje, na istoj je karti lako odrediti i označiti sječnu liniju. Procjenu raspodjele prsnih promjera stabala u sječini moguće je lako izlučiti iz baze podataka prostornoga položaja stabala, uz pretpostavku postojanja povezanosti visine i prsnoga promjera stabala.

Međutim, još uvijek ima prostora za poboljšanja, kao što je usporedba rezultata dobivenih s LiDAR-ovih snimaka i terenskih izmjera podataka, unapređenje metoda prepoznavanja stabala temeljenih na LiDAR-ovim snimcima, unapređenje procjene sortimentne strukture na temelju prsnoga promjera i visine stabala ili matematičko formuliranje i definiranje rasporeda sječnih jedinica.

Ključne riječi: LiDAR, prepoznavanje parametara stabla, Voronoiev mozaik, planiranje sjekoreda, planiranje pridobivanja drva

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