Lesn. Cas. For. J. 62 (2016) 146–151

DE GRUYTER OPEN

DOI: 10.1515/forj-2016-0017

Lesnícky časopis - Forestry Journal
http://www.nlcsk.sk/fj/

ORIGINAL PAPER

Spatial considerations of an area restriction model for identifying harvest blocks at commercial forest plantations

Jan Kašpar[1]*, Gerardo F. E. Perez[2], Adelaide Cerveira[3], Róbert Marušák[1]

[1]Czech University of Life Sciences Prague, Faculty of Forestry and Wood Sciences, Kamýcká 129, CZ – 165 21 Prague 6 – Suchdol, Czech Republic
[2]Universidade Federal do Paraná (UFPR), Rua dos Funcionários, 1540, Juvev) – Curitiba – Paraná, Brazil
[3]University of Trás-os-Montes e Alto-Douro, 5001-801, Vila Real and INESC TEC, Portugal

Abstract

In the past few decades, ecological and environmental issues have dominated the forest industry worldwide, but economic aspects have been much less studied in this dynamic period. However, a sustainable and efficient forest biomass supply is critical for socio-economic development in many regions, particularly in rural areas. Nature protection efforts have contributed to reduced harvesting quotas, which have resulted in an imbalance of the environmental functions of the forests and forest management, particularly wood supply.

Considering the size and distribution of forest production management units and the forest stands that compose those units, there is a clear need for improved decision-making tools that help forest managers in planning harvest sequences. The optimization of harvest scheduling should consider economic and spatial factors, which may reduce production costs by increasing the logistic efficiency. Moreover, incorporating maximum harvesting opening size constraints into planning can help preserve biodiversity.

This article presents a new spatial harvest scheduling model based on the integer programming method; it was developed using real data from a forest production unit located in the northern part of the southeast region of Brazil. The goal of the proposed scheduling approach is to maximize the net present value and concentrate the harvesting locations in each period. In spite of the fact that the object of the study is plantation forest under management different to common conditions in Europe or North America, the model is flexible and can be used in management of forest in Central Europe.

Keywords: Eucalyptus; plantation management; spatial harvest scheduling; harvest-flow constraints

Editor: Bohdan Konôpka

1. Introduction

The importance of exact mathematical methods in decision-making processes is indisputable, especially in forest management, which is faced with very complex scenarios due to the spatial and temporal aspects of decision models with many sources of uncertainty. Furthermore, forest managers often have to find a balance between goals of multiple participants (owner, public society, nature protection organizations, etc.) in most cases.

According to Baskent & Keles (2005), forest planning can be defined as the organization of the various activities to be undertaken over time in a forest to meet the objectives of the project, while also ensuring long-term sustainability of forest resources and the steady flow of wood products. Buongiorno & Gilles (2003) recognized that the strategic planning of wood production involves managing large forested areas, and many operations and people; often different aspects of the production process compete for the same resources, which makes the allocation of this resources a complex task. Thus, to achieve a satisfactory return on investment, it is necessary to implement a detailed forest management plan efficiently allocating production factors to achieve the established objectives. According to Falcão & Borges (2003), management models that consider the geographical locations of forest activities contribute to avoid segregation across levels of strategic and operational planning. They can also provide necessary information to address problems related to the transport of forest products and / or the spatial arrangement of cultural operations.

A key aspect of spatial forest planning is the combination of optimal harvest scheduling with the spatial dispersion of harvesting units; variations in either of these factors involve not only environmental impacts, but also consideration of operational logistics. Scheduling of forest harvesting involves identifying a series of areas to be cut to ensure maximum profit for the landowner and guarantee a balance in the harvested amount of wood or area over a defined period. However, more traditional forest planning methods did not consider spatial dispersion of harvesting units, so it is difficult to evaluate the tradeoffs of a harvest plan in terms of logistical and environmental impacts versus financial goals.

By introducing spatial variables in forest planning problems, it is possible to find an optimal solution between economic, environmental, and logistical objectives within the constraints provided. According to Öhman & Eriksson (2010), including spatial parameters in strategic planning of forest harvesting increases its complexity. One reason for the increased complexity is that to represent the aggregation of management units into the models, integer variables need to be

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**Corresponding author. Jan Kašpar, e-mail: kasparj@fld.czu.cz, phone: +420 22439 3796*

introduced to specify the type of management regime that will be applied to each unit; in addition, specific information about adjacent units also needs to be considered, not solely for each isolated harvest unit.

In traditional unit restriction models (URM), harvest clusters are formed *a priori* by the forest planner (Murray 1999). This approach is often used in countries where laws limit the size and/or shape of harvest units (Kašpar et al. 2016). Underestimation of objective function values is one of the major disadvantages of URM (Richards & Gunn 2000). However, Hokans (1983) and Lockwood & Moore (1993) proposed a modelling approach to create harvest clusters during the optimization process; this approach is referred as the area restriction model (ARM). One of the possible exact integer programming formulations is called the *Path formulation*, originally proposed by McDill et al. (2002), which is based on enumerating all feasible clusters that cannot be harvested as a whole and which are minimal. Each of these clusters is a continuous group of stands with total area exceeding the limit size and does not contain any cluster with area exceeding the limit size. So, it is necessary to remove only one of the stands, in such a cluster, before it becomes feasible (Crowe et al. 2003), that is, if $|C|$[1] is the cardinality of cluster C then at most $|C| - 1$ of them can be harvested simultaneously. We consider that two sands are adjacent if the boundary that they share is not a discrete set of points.

Harvesting units sparsely dispersed in a forest management area have lower environmental impacts because they present fewer problems related to erosion after harvesting and they promote wildlife protection. However, this dispersion may cause logistical problems in the harvesting and transport of the timber, thus increasing production costs. So, in reality, environmental and economic goals often conflict with one another; we attempt to find a compromise between them by using a maximum distance constraint and creating clusters of harvest units.

The complexity of spatial forest planning requires mathematical models and techniques within decision support systems that consider adjacency restrictions. The Decision support system (DSS) Optimal, developed for Central Europe forest management conditions, has been presented in several previous papers (Marušák & Kašpar 2015; Marušák et al. 2015; Vopěnka et al. 2015). The DSS Optimal is a powerful tool used in the Czech Republic for harvest scheduling. Because DSS Optimal uses Java SDK for ArcGIS desktop extensions, it is easily modified to include different spatial constraints.

The goal of this paper is to present a basic harvest scheduling model in the context of plantation management conditions in Brazil. We also present results of analyses based on alternative initial conditions. The model has been implemented into an updated version of DSS Optimal tool applied in countries of Central Europe. The newly developed DSS tool was used to analyze the alternative harvest scheduling scenarios.

2. Material and methods

2.1. Model

A very simple area restriction harvest scheduling binary programing model was created for the purpose of our case study. The model is presented in Equations 1–7:

$$\text{Maximize} \sum_{i=1}^{N}\sum_{p=1}^{P} c_{ip}x_{ip} \qquad [1]$$

subject to:

$$\sum_{p=1}^{P} x_{ip} \leq 1 \;\; \forall i=1,\dots,I \qquad [2]$$

$$x_{ip} + x_{jp} - 2z_{ijp} \geq 0 \qquad [3]$$

Maximum distance constraints:

$$d_{ij}z_{ijp} \leq D \;\forall\; z_{ijp} \qquad [4]$$

Harvest volume-flow constraints:

$$(1-\propto)\sum_{i=1}^{N} v_i x_{i(p-1)} \leq T \leq (1+\propto)\sum_{i=1}^{N} v_i x_{i(p-1)} \;\; \forall\, p = 1,\dots,P \qquad [5]$$

Maximum opening size constraints:

$$\sum_{i\in C} x_{ip} \leq |C| - 1 \;\forall\; C \in \Im \qquad [6]$$

$$x_{ip} \in \{0,1\} \;\forall\, p = 1,\dots,P;\, i = 1,\dots,N$$
$$z_{ijp} \in \{0,1\} \;\forall\, p = 1,\dots,P;\, i,j = 1,\dots,N, i < j \qquad [7]$$

The objective function [1] maximizes the net present value (NPV) from all harvested forest stands, $i = 1, \dots, N$, and from all planned years, $p = 1, \dots, P$, while the c_{ip} parameter expresses the NPV from harvested wood in Euro (€), and x_{ip}, for $i = 1, \dots, N$ and $p = 1, \dots, P$, is the decision variable that takes value 1 if stand is harvested in period p and 0 otherwise. The first constraint, equation 2, ensures that each unit is harvested only once during the planning horizon. Equations 3 and 4 ensure the distance between selected stands, d_{ij}, calculated as a Euclidean distance between centroids of stands i and j, is less than parameter D, the maximum distance allowed between those stands. The z_{ijp}, for $p = 1, \dots, P$; $i, j = 1, \dots N$, $i < j$, are decision variables taking value 1 if both stands i and j are harvested in period p and 0 otherwise. Equation 5 ensures an annual balanced harvest volume throughout the planning horizon. A harvest volume is allowed to vary by $\propto$(%) from one period to the next. The T variable is a new general variable that defines the potential harvest level for each year, and v_i is the absolute value of the wood volume of stand i. The constraint (6) are known as the path constraints, impose area limit in the opening areas. These constraints prohibit to harvest too large clusters, that is, clusters whose area exceed the imposed area limit. The set $\Im$ consists of all possible minimal infeasible clusters, that is, all possible clusters that cannot be harvested as a whole and are mini-

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[1] $|C|$ denotes the cardinality of set C, that is the number of elements of set C.

mal. They assure that from each cluster C in set $\Im$ we can harvest at the same period at most $|C|| - 1$ stands, being $|C|$ the cardinality of set C, that is, it is necessary to remove only one stand from the set C before it becomes feasible. Finally, the constraints (7) impose that all variables are binary.

2.2. Case study

We used spatial and numerical data from a timber farm in north of the southeast region of Brazil for this study. The farm belongs to a private entity, thus we do not specify the location or the name of the farm. The total area is 2412 hectares and the number of forest stands is 105 (N) were their areas ranging from 1.07 hectares to 24.50 hectares with average value equal to 22.97 hectares. The location of this timber farm is presented in Fig. 1. The timber farm is on the border of two geographical regions - Cerrado and Mata Atlântica. There is a prevailing tropical climate, which influence the eucalyptus production of 30 – 40 m^3/hectare/year.

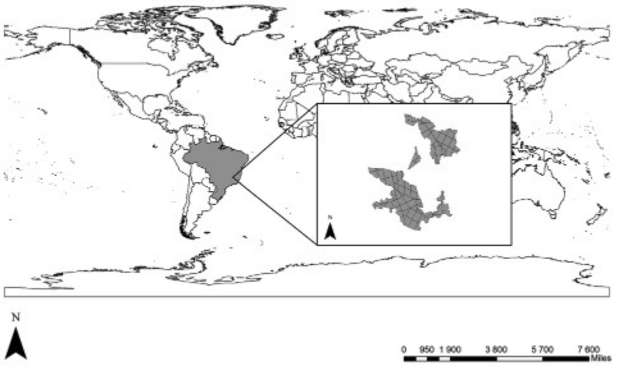

Fig. 1. The location of the timber farm in Brazil.

Exlusively, *Eucalyptus urophylla* S.T. Blake, is planted at the timber farm while the wood would be used for commercial purposes, such as construction, power generation, furniture making, charcoal, pulp and paper production. Stands are harvested when the MAI (Mean Annual Increment) curve crosses the CAI (Current Annual Increment) curve; for *E. urophylla*, this occurs between 6 and 8 years of age. Stands younger than 5 years old cannot be harvested, and stands older than 8 years old are prioritized for harvesting. Age, site index, and stand volume data for all stands in each year were available.

We used several combinations of the following parameters to conduct the analysis, including: D=2.5 km, 5 km, and 10 km; $\propto$ = 5%, 10%, and 15%; and, C was tested at 25 ha, 50 ha, and 75 ha) were analyzed. The different combinations of these alternative parameters were compared against the results of a null scenario that used no maximum distance between harvested stands in a given year (D), no limits on the percentage of volume harvested from year-to-year ($\propto$), and no opening size constraints (C)

The total NPV of the 5-year planning horizon (P) was calculated for each scenario. The price of harvested wood, harvest costs, and silviculture costs are included in the NPV calculation; all monetary values are presented in Euro (€). The real prices of wood at the timber farm as well asreal Brazil interest rate of 14% were used for all analyses. The effects of different management conditions and input parameters on total NPV were evaluated.

3. Results

The final results of are presented in Tables 1 – 5. The objective function values (total NPV) of the different alternatives are presented in Tables 1 – 4, which display scenarios with no maximum opening constraints, 75-ha maximum opening constraints; 50-ha maximum opening constraints, and 25-ha maximum opening constraints. A comparison of the objective functions of all scenarios relative to the null scenario is presented in Table 5.

The highest potential objective function value, € 21,783,770, was found in the no maximum opening size, maximum distance, and harvest volume flow constraint scenario (Table 1). All other alternatives´ objective function values were lower (Tables 1 –4), which simply means that constraints on any of these factors limit the objective function value.

Maximum opening constraints and harvest volume flow constraints had the smallest effect on objective function values; the maximum distance constraints had the greatest impact on NPV. However, the constraints also displayed a synergistic effect; the maximum distance constraints most negatively decreased the objective function values when the maximum opening constraint was 25 ha.

As it can be seen in tables 1 to 4, the objective function value coincide without considering constraints about the maximum distance and considering 10 km as the maximum distance. It means that without constraint in the distance between the opening areas we get already a solution where the distance between them are less or equal than 10 km. Furthermore, in that solution the distance between some of the opening areas are greater than 5 km and so, with D = 5 km, the objective value decreases.

Table 1. NPVs (expressed in Euro) with no maximum opening size constraints using alternative harvest volume flow and maximum distance constraints in an area restriction harvest scheduling binary programing model.

Harvest volume-flow constraints	Maximum distance constraints no	 D= 10 km	 D= 5 km	 D= 2,5 km
no	€ 21,783,770	€ 21,783,770	€ 21,611,032	€ 20,312,147
$\propto$ = 15%	€ 21,709,180	€ 21,709,180	€ 21,524,723	€ 20,218,849
$\propto$ = 10%	€ 21,688,842	€ 21,688,842	€ 21,495,634	€ 20,096,002
$\propto$ = 5%	€ 21,662,521	€ 21,662,521	€ 21,472,272	€ 19,997,284

Table 2. NPVs (expressed in Euro) with 75-ha maximum opening size constraints using alternative harvest volume flow and maximum distance constraints in an area restriction harvest scheduling binary programing model.

Harvest volume-flow constraints	Maximum distance constraints no	 D= 10 km	 D= 5 km	 D= 2.5 km
no	€ 21,775,739	€ 21,775,739	€ 21,333,623	€ 19,500,606
$\propto$ = 15%	€ 21,698,958	€ 21,698,958	€ 21,224,200	€ 19,230,089
$\propto$ = 10%	€ 21,674,122	€ 21,674,122	€ 21,190,465	€ 19,171,129
$\propto$ = 5%	€ 21,647,094	€ 21,647,094	€ 21,155,801	€ 18,934,139

Table 3. NPVs (expressed in Euro) with 50-ha maximum opening size constraints using alternative harvest volume flow and maximum distance constraints in an area restriction harvest scheduling binary programing model.

Harvested volume-flow constraints	Maximum distance constraints no	*D* = 10 km	*D* = 5 km	*D* = 2.5 km
no	€ 21,619,031	€ 21,619,031	€ 18,890,391	€ 14,564,865
∝ = 15%	€ 21,570,390	€ 21,570,390	€ 18,882,110	€ 14,557,164
∝ = 10%	€ 21,559,932	€ 21,559,932	€ 18,865,260	€ 14,544,095
∝ = 5%	€ 21,546,020	€ 21,546,123	€ 18,819,400	€ 14,520,904

Table 4. NPVs (expressed in Euro) with 25-ha maximum opening size constraints using alternative harvest volume flow and maximum distance constraints in an area restriction harvest scheduling binary programing model.

Harvested volume-flow constraints	Maximum distance constraints no	*D* = 10 km	*D* = 5 km	*D* = 2.5 km
no	€ 21,743,614	€ 21,466,606	€ 16,980,118	€ 12,539,383
∝ = 15%	€ 21,433,964	€ 21,433,964	€ 16,934,360	€ 12,520,616
∝ = 10%	€ 21,421,127	€ 21,421,127	€ 16,907,691	€ 12,520,616
∝ = 5%	€ 21,405,127	€ 21,405,127	€ 16,819,627	€ 12,480,796

The relative differences (%) in the NPV for all alternatives compared to the scenario without a maximum opening size, maximum distance constraint, and harvested volume-flow constraint (€ 21,783,770) are presented in Table 5. The values were divided into four groups to identify stronger effects on NPV, which confirms the previously discussed importance of each constraint. The range between 99% – 100% is green; 91% – 98% is yellow; 81% – 90% is orange and less than 80% is red. Moreover, this type of results´ presentation can be very helpful in decision process since the simplicity of data presentation.

Table 5. The relative differences (%) in the objective functions for all alternatives compared to the scenario without a maximum opening size, maximum distance constraint, and harvested volume-flow constraint: A) no maximum opening size constraint; B) 75-ha maximum opening size constraint; C) 50-ha maximum opening size constraint and D) 25-ha maximum opening size constraint.

	A)				B)			
Harvest volume-flow constraints	Maximum distance constraints no	10 km	5 km	2.5 km	no	10 km	5 km	2.5 km
no	100%	100%	99%	93%	100%	100%	98%	90%
∝ = 15%	100%	100%	99%	93%	100%	100%	97%	88%
∝ = 10%	100%	100%	99%	92%	99%	99%	97%	88%
∝ = 5%	99%	99%	99%	92%	99%	99%	97%	87%

	C)				D)			
Harvest volume-flow constraints	Maximum distance constraints no	10 km	5 km	2.5 km	no	10 km	5 km	2.5 km
no	99%	99%	87%	67%	98%	99%	78%	58%
∝ = 15%	99%	99%	87%	67%	98%	98%	78%	57%
∝ = 10%	99%	99%	87%	67%	98%	98%	78%	57%
∝ = 5%	99%	99%	86%	67%	98%	98%	77%	57%

The spatial distribution of harvested stands from the scenario examining 25-ha maximum opening size constraint, 5% harvest volume flow constraint, and 2.5 km maximum distance constraint is displayed in Fig. 1. The harvested stands within each year of the planning horizon are generally close to one other, which could potentially help minimize transportation costs. The maximum opening constraint did not allow for harvested stands to occur in large contiguous areas. In this case, as the area of forest stands are big when compared with the maximum opening area, the obtained opening areas doesn't contain many forest stands.

The spatial distribution of harvested stands from the scenario with no maximum opening size constraint, no harvest volume flow constraint, and no maximum distance constraint is displayed in Fig. 3. Compared to Fig. 2, no maximum opening size constraints and maximum distance constraints created large contiguous harvested areas in years 1 and 2, but over the rest of the planning horizon the harvested stands are more dispersed throughout the management area, which would potentially result in much higher transportation costs. In this solution all the forest is harvested during the planning horizon which could compromise the forest sustainability due the fact that the planning horizon has 5 years and the species considered should be harvested around 7 years of age. That situation doesn't occurs in the solution presented in Fig. 2. Depending on the goal of the forest managers they could follow one of the proposed planning management. Refer that Table 5 is good to see the relations between percentages of harvest flow and maximum distance.

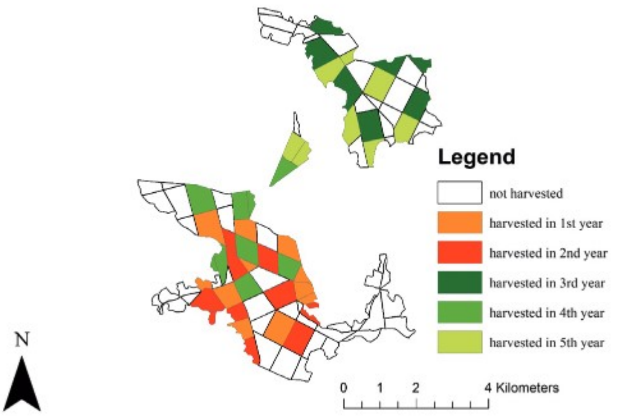

Fig. 2. The resulted spatial distribution of harvested stands by alternative 25 hectares maximum opening constraints, 5% harvested volume-flow constraints and 2.5 kilometers maximum distance constraints.

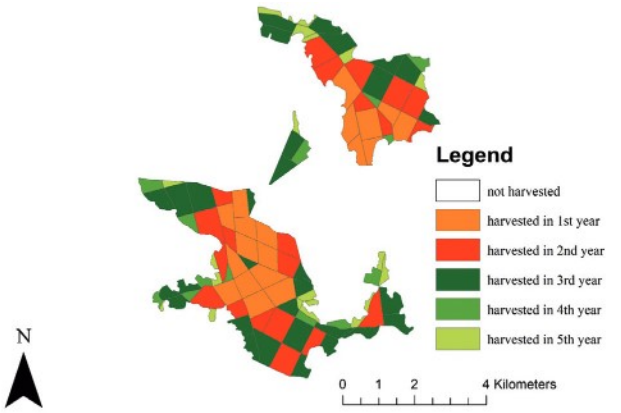

Fig. 3. The resulted spatial distribution of harvested stands by alternative without maximum opening constraints, harvested volume-flow constraints and kilometers maximum distance constraints.

4. Disccusion

This paper presents the effects of two different spatial constraint types, maximum distance and maximum opening size, used in a harvest scheduling area restriction model. Maximum distance constraints encourage the creation of clustered spatial harvest blocks, which helps minimize associated transportation costs (economic aspect), and maximum opening size constraints limit the size of clear cuts (environmental aspect). The harvest volume flow constraints are inherent parts of any harvest scheduling model and contribute to both economic and environmental aspects of harvest planning.

Many researchers have examined the economic aspects of different management approaches (for example, Tiernan & Nieuwenhuis 2005 or Emmingham et al. 2002). In coincidence with other studies (see for example, Crowe et al. 2003), positive influence of maximum opening size on NPV was confirmed in our study. In addition to this, negative impact constraints on NPV is evident in this study, similar to the findings of Borges et al. (2015). The use of ARM in managed forests of central Europe is problematic because of the shape of harvest units´ legaly limitations (Kašpar et al. 2016). However, as Richards & Gunn (2000) demonstrated, URM are also subject to harvest units´ legaly limitations, which could underestimate NPV. Murray & Weintraub (2001) estimated the difference could be as high as 16.5%. On the other hand, if NPV was the only constraint in the planning process, clear cut sizes would likely present environmental problems (e.g., erosion, wind damage). The size and shape of clear cuts is important in managing risk of wind damage (Zeng et al. 2004, 2009).

It is required to include orientation of harvest units in the model to reduce the effect of climatic conditions (wind) at the edge of the stand (Konôpka & Konôpka 2008). Many other conditions should be incorporated into the model if it is to be willingly adopted in Central Europe. For instance, the shelterwood management system is an increasingly used silvicultural prescription in Central Europe and there are few papers that deal with spatial harvest scheduling under shelterwood management systems (see for example Marušák & Kašpar (2015)). Another important difference between plantation and managed forests in Central Europe is the length of crop rotation periods. The rotation of managed forests in Central Europe is over 100 years in most cases, compared to only a period of 6 to 8 years, as presented in this study. The longer the rotation period, managers will have to contend with greater risk and uncertainty related to forest growth and also concerns about long-term health and stability of forest stands (Pasalodos-Tato et al. 2013). Stand characteristics play an important role in lowering the risk of windthrow events (Lohmander & Helles 1987). Nevertheless the principle of the presented model is fully flexible to use in different spatial conditions by slight modification, which take into account specific management conditions. It makes the model utilizable in Central Europe region but also in other management systems which are using optimization techniques. Following this the model can be used to analyze the currently used clear cut size, shape, and adjacency constraints in managed forests of Central Europe.

The maximum distance constraints played an important role in the economic aspects of the model. Unfortunately, this approach did not consider forest roads and associated routes, so the creation of harvest blocks is only hypothetical and does not include the high capital costs of forest road building (Bruce et al. 2011). It would be necessary to use an extended type of model that includes minimizing transportation infrastructure construction costs and more detailed information about transportation costs (see for example Palma, Nelson (2013)). Nevertheless, as a general rule, the total harvest costs increase and productivity decreases with increased transportation distances (Spinelli et al. 2004). It is evident that concentrating harvesting activities will produce lower transportation infrastructure construction costs. However, this method can offer a spatial analysis of alternative harvest scenarios, or in areas without developed road networks, such as the timber farm presented in this case study. Maximum opening size had a lesser effect than the maximum distance constraints on NPV. No maximum opening size constraints produced similar NPV compared to the most restrictive maximum opening size constraint (25 ha).

It is necessary to mention that presented results are valid for specific spatial configuration of these forest stands, the assumed timber prices and interest rates, and the rapid growth of E. urophylla. However, based on the previous experience of the authors, one can assume that the general trends of our results will be similar even if other input data and proposed models were used in different management conditions.

5. Conclusions

Our study examined the question of whether considering different spatial aspects (economic and environmental) in forest harvest scheduling would have a significant influence on the total NPV of timber, one of the primary goals of every forest manager.

We presented different alternative constraints and concluded that including maximum opening size area limitation (environmental aspect) will reduce total NPV, but not to the same degree as the maximum distance limitation (economic aspect). Nevertheless, it is evident that the greater number of management goals included in harvest planning (presented as constraints), the more complex the harvest scheduling problem becomes, and that exact mathematical methods and computer tools are needed to find the optimum balance of the desired goals.

Since the presented model is flexible, it could be used also for plantation management in Central Europe. Its implementation in a variety of managed forests is specifically possible by the means of changed model´s parameters (length of period, tree species, growth function etc.). The resulted values will be different in case of lower interest rate (0.5 – 2% usually used in Central Europe), however, the general relationships will remain the same.

Acknowledgments

This research was supported by the projects of the National Agency for Agriculture Research (No. QJ1320230 and No. QJ1330233) and the Internal Grant Agency of Faculty of Forestry and Wood Sciences Czech University of Life Sciences in Prague (No. B07/15).

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