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Spatial and non-spatial harvest scheduling versus conventional timber indicator in over-mature forests

Prostorové a neprostorové plánování těžeb versus tradiční těžební ukazatelé v lesích s přestárlou věkovou strukturou

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Abstract

This paper presents two alternative approaches of final cut scheduling for a fifty year strategic planning horizon. One approach is represented by cutting percentage, which is a classical timber indicator commonly used in the Czech and Slovak Republics. The second approach is represented by two optimisation models of integer programming; the first model without spatial aspect and the second model including adjacency constraints. Both optimisation models are derived for the clear cut management system with the scheduling approaches applied on an example of a forest management area with over-mature stands.

The main aim of the paper is to compare two suggested optimisation models with the classical scheduling approach and to demonstrate their positive effect on the age class distribution of forests. The further aim is to include green-up constraints in the scheduling, which respect legislative conditions. The results show that even in the case of a single management system, without considering different ecosystem services, the optimisation model that does not consider the spatial aspect gives comparable results to the approach that r includes the adjacency constraints. The primary hypothesis, that the regular age-class distribution and flow harvesting cannot be achieved when considering green-up constraints, was rejected.
Keywords: harvest scheduling; integer programming; age-class distribution; adjacency constraints

Abstrakt

Práce prezentuje dva alternativní přístupy k plánování mýtních těžeb v rámci 50 letého strategického plánovacího horizontu. Jeden přístup je reprezentován klasickým těžebním ukazatelem, těžební procento, který je běžně používaný v České a Slovenské republice. Druhý přístup je reprezentován dvěma optimalizačními celočíselnými modely; první model je bez prostorového aspektu, druhý pak zahrnuje vztahy omezení sousednosti. Oba dva optimalizační modely jsou odvozeny pro holosečný hospodářský způsob. Alternativní přístupy plánování těžeb jsou aplikovány na příkladu lesního hospodářského celku s převahou přestárlých porostů.

Hlavní cíl práce je porovnat navržené optimalizační modely s klasickým postupem plánování mýtní těžeb a demonstrovat pozitivní vliv navržených těžeb těmito modely na věkovou strukturu lesa. Dalším cílem je zahrnout do modelu zákonná omezení vzájemného přiřazování holých sečí. Výsledky ukazují, že i v případě jednoduchého hospodářského způsobu bez zahrnutí různých ekosystémových služeb, poskytuje optimalizační model bez prostorového hlediska srovnatelné výsledky s modelem, který tato hlediska zahrnuje. Primární hypotéza, že nemůže být dosaženo normální věkové struktury a těžební vyrovnanosti i v případě použití omezení týkající se přiřazování sečí, byla zamítnuta.
Klíčová slova: těžební plánování; celočíselné programování; věková struktura; omezení sousednosti

1. Introduction

Forest management and in particular, harvest scheduling has been influenced by two decades of socio-economic, political and natural changes in central Europe. Following political changes in 1989, forest privatisation caused changes in forest ownership with the state sector now owning only 59.8% of the forest area in the Czech Republic (Green Report 2012). This forest fragmentation has reduced the average size of the forest management area (FMA) since 1989.

The second driver of forest management is related to shifting public preferences (Šišák 2011) and especially the management of non-productive forest functions, such as recreational and hygienic functions. Forest managers have to take these non-productive forest functions into consideration and react accordingly by changing their management approach.

A further challenge for forest management is to consider the potential consequences of climate change. The Intergovernmental Panel on Climate Change (IPCC WG II 2007) predicts that changing climate in Europe is likely to increase the frequency of large wind-throws, both from increased storm frequency and increased water stress, while at the same time decreasing the average defence capability of the remaining trees through spring temperature backlashes and summer water stress (Schlyter et al. 2006). For instance, abiotic disturbance agents such as wind, snow etc., caused 65% of salvage felling in the Slovak Republic between the years 2002–2006 (Konôpka & Konôpka 2008). Open areas in forests such as clear cuts, affect the wind speed.

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The effect of forest fragmentation, which can be caused by clear cut management system, was studied by Zeng et al. (2009). The authors concluded that forest fragmentation may increase the susceptibility of forest stands to wind damage. New approaches to harvest scheduling management are needed especially in the areas with a high risk of wind damage (Konôpka & Konôpka 2009). Konoshima et al. (2011) present one kind of harvest scheduling approach based on integer programming. Finally, from the ecological point of view and also due to the above-stated reasons, there is legislation determining the localisation of two clear cuts performed at the same time, their maximum size and width. These requirements vary between countries and are highly dependent on the relevant laws.

At present there is one timber harvesting indicator for small forest management areas (less than 500 hectares) implemented in the Czech legislation. This expresses the maximum possible final cut and is known as the cutting percentage (hereafter referred to as CP). The indicator comes from the normal forest as described in Bettinger et al. (2009). However, a regulated forest with a balanced and regulated age-class distribution is not only difficult to achieve, but also undesirable for forest stability (Priesol & Polák 1991). In addition, the CP indicator is static, incorporating planning for one decade only, without the option to account for harvesting possibilities over a longer time period and does not consider the spatial possibilities of harvesting. This results in strongly uneven decadal harvests for the whole forest management area (FMA) from the view of strategic future harvest planning.

For the reasons mentioned, there is an increasing need to analyse the development of spatial structure because without the spatial aspect, it is impossible to maintain environmental, social and other aspects of forest management (Baskent & Keles 2005.

Methods of operational research in conjunction with modern information technology and geographic information systems (GIS) can be used to create a new type of forest management plans. What makes spatial forest-management plans different from conventional plans is the proposal of size, shape and position of forest harvest units in the forest management area.

Simple linear programming models for harvest scheduling without spatial aspects with varying constraints are presented in many papers and textbooks (e.g. Bettinger et al. 2009; Buongiorno & Gilles 2003). However, there are no obvious comparisons of timber indicators which are used in the conditions of central Europe, especially in the Czech Republic and Slovakia. Research works aimed on harvest scheduling optimisation are rare in this region. Marušák (2007) compared different classical timber indicators used in Slovakia with the spatial linear model of harvest scheduling. Unfortunately, the author does not compare his spatial models with relevant non-spatial models; therefore, the importance of the spatial aspect for harvest scheduling is not obvious in this case. Kouba & Zahradník (2004) present another example of using linear programming model to obtain the information on the target age class distribution.

The aim of this paper is to present the impact of adjacency constraints on harvest possibilities in a real management forest area with undesirable age-class distribution. The suggested scheduling approach is presented in a clear cut management system. Only one type of adjacency constraints was used, so called green-up constraints (Buongiorno & Gilles 2003) because this is the basic spatial requirement defined by the forestry act. The primary hypothesis is that the regular age class distribution and harvesting balance cannot be achieved when considering green-up constraints.

2. Material and methods

The proposed approaches in strategic management planning were applied to a FMA of 178 ha (Fig. 1) located in Central Bohemia within Nature forest area No. 9 (according to forestry act), 60 kilometres west from Prague. Bedrock consists of sandstone, siltstone and claystone. The dominating soil is sandy-loam Cambisol. Spruce is a dominant tree species, its average site index is 28. As it is a private FMA, more detailed information cannot be provided to follow user rights. This FMA has a non-regulated age-class distribution with a high proportion of over-mature forest age classes (Fig. 2.). Age class span 10-year intervals (e.g. age class 1 consists of forest stands aged from 1 to 10 years, age class 2 consists of forest stands aged from 11 to 20 years etc.).

The planned strategic horizon of 50 years was divided into five 10-year-long intervals. Species composition of the forest stands has been simplified to one species (Norway spruce) only. To predict the growing stock, the growth model from the Czech yield tables was used (Černý et al. 1996).

The maps from the forest management plan were digitised and analysed in ArcGIS (ESRI 2014). All forests of the FMA that are in the cutting age or will reach the cutting age in the next 50 years were selected. For this purpose, the rotation age of 110 years and the regeneration age of 30 years were used for the entire FMA. There are 4 mature age classes for the combination of regeneration age (30 years) and rotation (110 years) in each planning period; 10^{th}, 11^{th}, 12^{th} and 13^{th} age classes are mature. Other older age classes are assigned as over-mature. The selected stands of the FMA were then divided into potential harvest units by the editing tools in ArcMap. When editing these units, wind direction, slope and existing logging roads were taken into account. Further, it was important to consider the legislative parameters for clear-cuts, primarily the maximum width equal to two mean heights of the surrounding stand with the maximum area of a clear-cut up to 1 hectare.

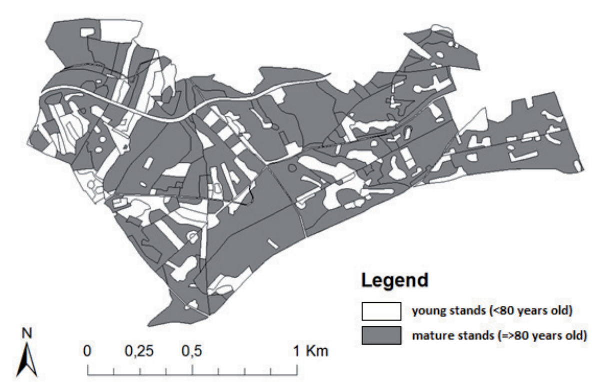

Fig. 1. The spatial structure of the forest management area.

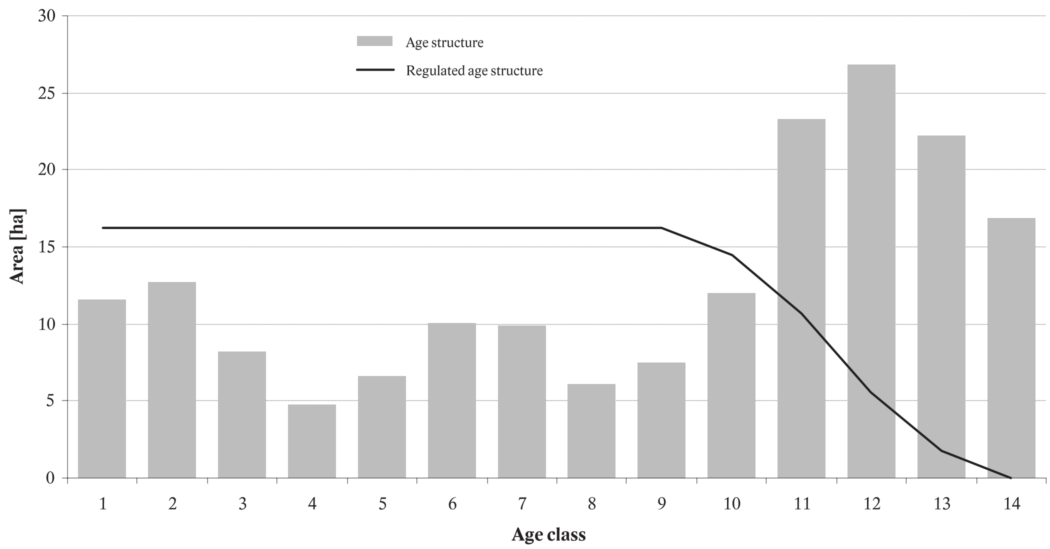

Fig. 2. The actual age structure of the forest management area.

Two optimisation models; one with and one without the spatial aspect, which represent alternative scheduling approaches, were developed. The first model is labelled as SPATIAL and includes the green-up constraints. The second tested model is labelled as NON-SPATIAL and does not include any green-up (adjacency) constraints. Both optimisation models are the extensions of the model proposed by Kašpar et al. (2013).

A forest management area consists of harvest units, each one with the homogenous structure indexed by of mature and over-mature age classes k. As this is a unit restricted model (Crowe et al. 2003), each binary variable in the model represents one proposed harvest unit designed for cutting or not over the P period.

Binary variables x are indexed by the harvest unit identifier; $i = 1, \ldots, I,$ period $p = 1, \ldots, P$ and age class $k = 1, \ldots, K.$

$$x_{ipk} = \begin{cases} 1 \text{ if the unit i of age class k will be cut in period } p \\ 0 \text{ in other cases} \end{cases} \qquad [1]$$

One of these constraints is that each unit can be cut just once per planned period. It can be generalised as:

$$\sum_{p=1}^{P} x_{ipk} \leq 1 \quad \forall i = 1,2,\ldots,n \qquad [2]$$

where n is the number of harvest units.

The harvest flow across the planning horizon is a necessary condition of harvest scheduling. This can be ensured by:

$$0.9\, V_{p-1} \leq V_p \leq 1.05\, A_N \qquad [3]$$

where V_p is the total harvest in period p. The condition of the harvested area flow in the each planning period can be expressed as:

$$0.95\, A_N \leq A_p \leq 1.05\, A_N \qquad [4]$$

where A_N is the area of theoretical clearing defined by the model of regulated forest and A_p is harvested area in period p.

The conditions that originate in the spatial relations between the harvest units can be set down using an analytic algorithm (Yoshimoto & Brodie 1994):

$$\boldsymbol{M}\, x \leq \boldsymbol{A}_p \text{ where} \qquad [5]$$

$$\boldsymbol{M} = \boldsymbol{A} + \boldsymbol{B} \qquad [6]$$

where $\boldsymbol{A}$ … adjacency matrix
$\boldsymbol{B}$ … diagonal matrix in which the ith diagonal element b_{ii} is defined by $b_{ii} = \boldsymbol{A}_i 1$
($\boldsymbol{A}_i$ is i-th row vector of adjacency matrix $\boldsymbol{A}$)
$\boldsymbol{M}$ … modified adjacency matrix
x … control vector for control variables x_{ipk}
1 … is an $(n \times 1)$ unit vector

The last set of conditions is used only in the case of the SPATIAL model. Finally, all harvest units cannot be harvested in each period. It depends on the regeneration age and rotation.

The objective function is the same for both SPATIAL and NON-SPATIAL optimisation models and is defined as:

$$\max V = \sum_{k=1}^{K} w_k \sum_{i=1}^{n} \sum_{p=1}^{P} V_{ipk} \cdot x_{ipk} \qquad [7]$$

where V is the total amount of final cut over five decades and w_k is the weight of k-th age class. V_{ipk} is the standing volume in harvest unit i in period p of age class k, n is the total number of potential harvest units in the FMA.

The weight for each mature and over mature class was defined: w_1 (for the 10th age class) is 0.15; w_2 (for the 11th age class) is 0.3; w_3 (12th age class) is 0.55; and w_4 (13th age class) is 1. All other over-mature age classes are represented by weight w_5 set to the value of 2. All of these values are set by expert estimation reflecting harvest preference of older mature and over-mature age classes. The total number of variables was approximately 1,400 and the number of constraints 1430. The problem was formulated as a classical *.lp file and solved by Gurobi 5.5.0 (Gurobi Optimization 2014). The problem was solved using a branch and bound algorithm which is a standard algorithm for solving mixed integer problems.

Finally, one further scheduling approach was used. It is the cutting percentage as described by (Priesol & Polák

1991) and represents the classical harvest scheduling and planning in the Czech and Slovak Republics.

The index of compliance I_{ZHr} (8, 9) and the overmature age class area ratio I_{PS} (10) (Marušák 2005) were calculated for each period and each scheduling approach to enable the objective valuation of age class distribution changes.

$$I_{ZHR} = 1 - \frac{\sum_{i=1}^{n} |\Delta|}{\Delta_{max}} \quad [8]$$

$$\Delta_{max} = |P - P_{N,j}| + \sum P_{N,k} \quad [9]$$

where P ... real area of mature and over-mature age classes

P_N ... regulated area of mature and over-mature age classes

j ... mature or over-mature age class with the lowest real area

k ... mature or over-mature age class with the larger area than age class j

Δ_{max} ... maximum difference

$$I_{PS} = \frac{P_{PS}}{P} \quad [10]$$

where P ... area of FMA

P_{PS} area of over-mature age classes

The index of compliance obtains values from 0 to 1. Absolute age-class compliance within a model of regulated forest resulted to value 1.

3. Results and discussion

The resulting scheduled harvest of SPATIAL and NON-SPATIAL variants are comparable from the view of total harvested amount, harvested area, index of compliance and the over-mature age class area ratio (Table 1, 2). The harvested area of both models is the same for each period and is in the upper limit of the relevant constraint. There is a slight difference in the total harvested volume of 112 m^3. The difference in harvest volume for each period of SPATIAL and NON-SPATIAL variants is negligible and corresponds with the conditions of harvest balance across the planning horizon.

The results are different in the case of the CP scheduling approach based on the normal forest assumption, which is reflected in the results. However, these results are valid only if the initial age class distribution is ideal or close to the ideal normal age class distribution; otherwise, the results are not ideal for non-normal forest and the other scheduling approaches are more relevant. The total harvested volume for the CP approach is over 20,000 m3 higher than for the SPATIAL and NON-SPATIAL models, but the harvested volume production is not stable in the CP approach and is reduced across the planning horizon (Table 1). The total cut achieved by the alternative scheduling approaches is not much different from the CP scheduling approach presented in the paper by Marušák (2007). However, the harvested volume production is also not stable in the CP scheduling approach.

The resulting values of index of compliance IZHr and the over-mature age class area ratio IPS calculated at the beginning of planning periods for each scheduling approach are presented in Table 2 as the suggested harvested volume is also known for the fifth period. The resulting age class distribution after five periods of harvesting for the SPATIAL, NON-SPATIAL and CP approaches are shown in Figures 3, 4 and 5.

The value of IPS after five periods of harvesting is very good in the case of the CP approach. The value of 0.00 indicates that there are no over-mature age classes. In the other two approaches, SPATIAL and NON-SPATIAL optimisation models, this value is 0.11 meaning that 11% of the total area consists of over-mature classes.

The index of compliance (I_{ZHr}) is 0.65 for both SPATIAL and NON-SPATIAL variants. The index of compliance for the initial state of age class distribution is 0.35, which means that the value of this index improved after five periods. The resulting age class distribution of the SPATIAL and NON-SPATIAL optimisation models is close to the ideal model of normal forest, much closer than the resulting age-class distribution of the CP approach. The final value of IZHr in the case of the CP approach is 0.18, i.e. worse than 0.35 of the initial age class distribution of the regulated forest model.

The original theory is that normal forests were developed to ensure sustainable and balanced harvesting. However,

Table 1. The resulting harvested volume and area for the three alternative models.

Scheduling approach	Period [years]	1–10	11–20	21–30	31–40	41–50	Total
SPATIAL	harvested volume [m^3]	16056	16421	16427	16378	16676	81958
	harvested area [ha]	17.8	17.8	17.8	17.8	17.8	89.0
NON-SPATIAL	harvested volume [m^3]	16282	16340	16297	16379	16770	82068
	harvested area [ha]	17.8	17.8	17.8	17.8	17.8	89.0
CP	harvested volume [m^3]	80069	8836	4122	4349	5266	102642
	harvested area [ha]	94.9	12.8	8.3	8.6	8.6	133.3

Table 2. The resulting index of compliance I_{ZHr} and the overmature age class area ratio I_{PS}.

Scheduling approach	SPATIAL		NON-SPATIAL		CP	
Period (years)	I_{ZHr}	I_{PS}	I_{ZHr}	I_{PS}	I_{ZHr}	I_{PS}
1–10	0.35	0.09	0.35	0.09	0.35	0.09
11–20	0.27	0.13	0.27	0.12	0.48	0.00
21–30	0.64	0.17	0.64	0.17	0.13	0.00
31–40	0.63	0.20	0.63	0.20	0.23	0.00
41–50	0.79	0.17	0.79	0.17	0.30	0.00
51–60	0.65	0.11	0.65	0.11	0.18	0.00

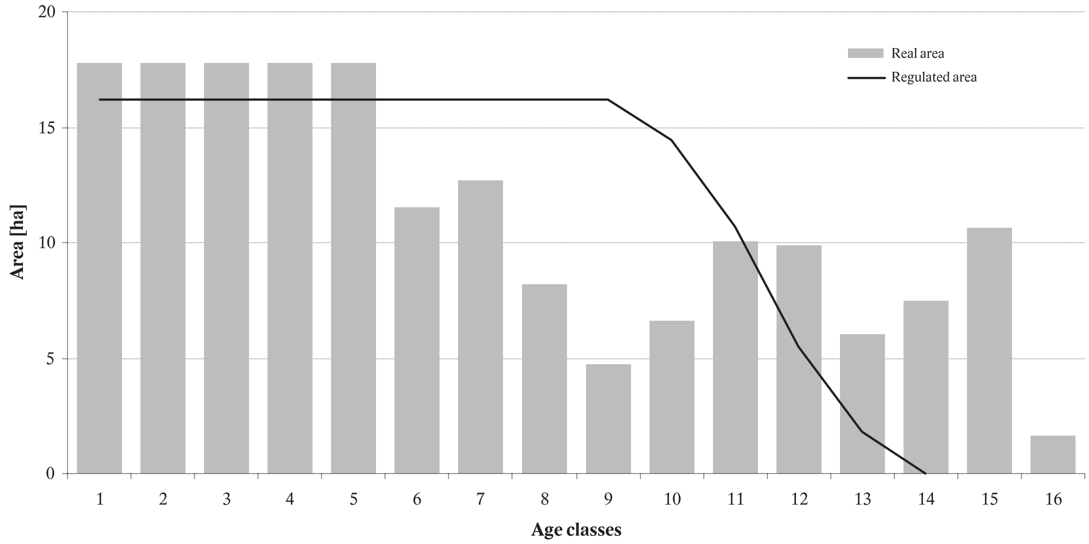

Fig. 3. The resulting age structure using SPATIAL model.

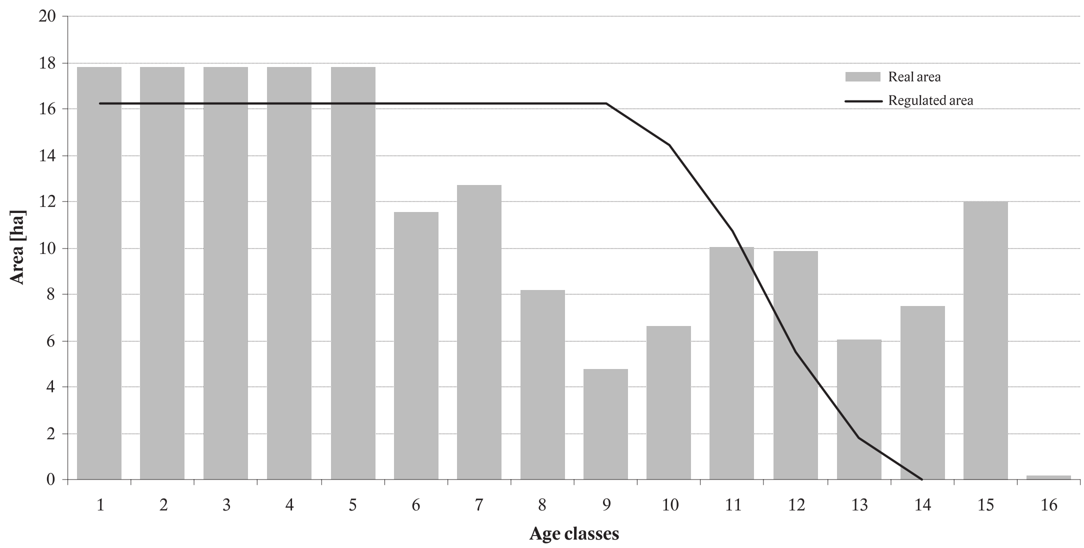

Fig. 4. The resulting age structure using NONSPATIAL model.

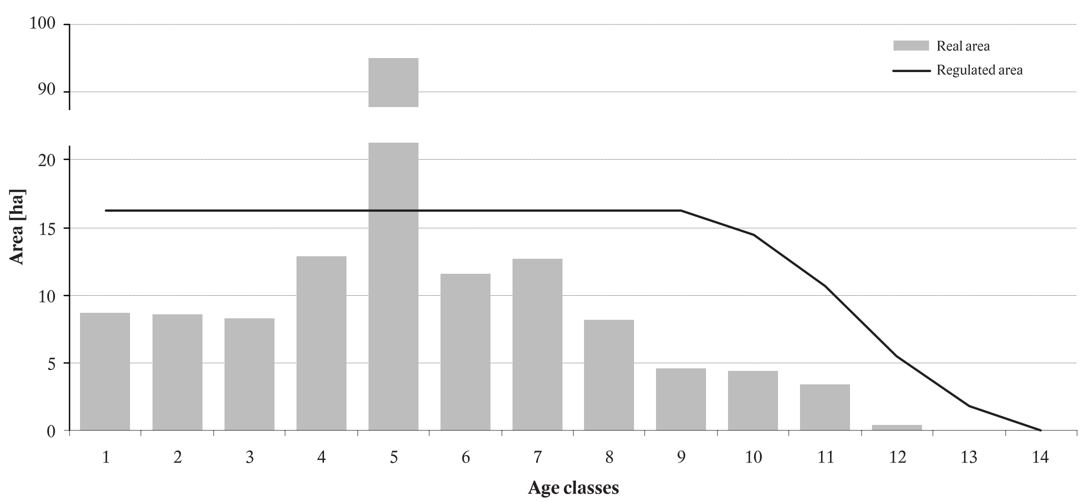

Fig. 5. The resulting age structure using CP approach.

timber indicators derived from this theory do not provide accurate results under changed political social and environmental conditions. This statement is based on the resulting age class distribution achieved by applying cutting percentage (Fig. 5). However, there are no over-mature age classes in the CP model due to the enormous harvested volume in the first planning period (80,068 m^3 / 94.9 ha). This indicates that early harvest intervention has an important effect on future harvest potential. An extensive area of just one age class is inappropriate from the perspective of forest protection and nature protection as well as biodiversity conservation.

The results achieved by SPATIAL and NON-SPATIAL models are comparable in the resulting age-class distribution. There is only a slight difference in the distribution of the harvested area in the last three age classes: 15^{th}, 16^{th} and 17^{th} (Fig 3. and Fig 4.).

Adjacency constraints in harvest scheduling approaches prevent adjacent management units from being scheduled for harvest within a given period and have practical importance of legal restrictions (McDill et al. 2002). However, harvest scheduling optimisation models with adjacency constraints are difficult to solve. It was expected by the research team that appropriate resulting age-class distribution cannot be achieved or alternatively the model run would be time-consuming in the case of the SPATIAL model because the parameters of adjacency are quite strict for model of the proposed harvest. The age-class distribution of the forest is one of the most important factors determining the solvability of scheduling problems with adjacency constraints. The impact of adjacency constraints on the different initial age--class distribution was studied by (McDill & Braze 2000). This problem can be worse in the case of over-mature or old--growth forests because a large number of harvests which would otherwise be scheduled would not be identified by the adjacency constraints. However, the presented results show that a good age-class distribution can be achieved, even in the case of the SPATIAL model when considering the mandatory adjacency constraints.

4. Conclusions

This paper presents modern scheduling approaches in comparison to a classical scheduling approach represented by cutting percentage. The volume of final cuts, when calculated by the current harvesting indicators, reflects only the current area or the volume of the cutting age classes. No information about age-class distribution or potential cuts on the evolution of the age-class distribution is taken into account. Current harvesting indicators apply to the normal forest only, which may be suitable for large areas of several thousands of hectares; however, in small forest areas, there is a growing probability that the age-class distribution is unbalanced due to which harvesting indicators lose their validity.

Furthermore, it seems that green-up constraints do not affect the harvest potential and that the age-class distribution is as expected. The primary hypothesis defined above could not be confirmed for the normal age-class distribution and harvest balance accounting for green-up constraints. The results can be considered basic for the inclusion of other adjacency constraints, such as nature reserve or recreational function of the forest, further added to mandatory adjacency constraints into the scheduling approach. Adjacency constraints are also important in the case of forest protection. However, this type of constraints must include special requirements such as creating of cutting segments that are protected against wind damage. The creation of a scheduling approach considering constraints mentioned above, would be an interesting extension of this paper. This type of a harvest scheduling problem has to be solved at a larger FMA because of the decreasing edge effect.

According to the achieved results, the use of these methods for optimisation of harvest planning does not only appear to be acceptable, but it also seems that in the context of the forests of the Czech Republic, it fits even better than the use of the classical harvesting indicators.

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