Nature Environment and Pollution Technology
An International Quarterly Scientific Journal

ISSN: 0972-6268	Vol. 15	No. 2	pp. 429-436	2016

Original Research Paper

Algorithms of Thinning Simulation for Timber Plantation - A Case Study of Chinese Fir

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Nat. Env. & Poll. Tech.
Website: www.neptjournal.com

Received: 24-03-2015
Accepted: 05-05-2015

Key Words:
Timber plantation
Thinning simulation
Forest harvesting
Algorithms
Chinese fir

ABSTRACT

Thinning parameters, such as stand initial density, thinning time, number of thinning, thinning interval, intensity, and cutting age, were analyzed; constraints of these parameters were established. Based on these parameters, two algorithms were proposed. One algorithm was used to calculate volume harvest based on thinning parameters to determine the function of the predicted stand volume harvest via various thinning strategies. The other algorithm was used to develop an enumeration iterative algorithm based on the largest volume yield that can be obtained via an optimal thinning strategy. A decision support system of thinning simulation based on these algorithms was developed. Growth and yield models related to Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook.) were selected as research examples. When the initial stand was 4000 stems per hectare, site index was 16 meters and cutting age was 30 years, the Chinese fir stand can yield at most 906.74 m^3/ha and 940.74 m^3/ha if thinned once and twice with the corresponding and proposed thinning strategies, respectively.

INTRODUCTION

Thinning is one of the most important issues among forest managers. Thinning also affects the growth of stand factors. In timber plantations, stand volume harvest is used to determine quantitative maturity in stand growth and yield prediction systems. However, various conclusions on how thinning activities can affect stand volume harvest have been presented because of differences in tree species, stand conditions, thinning systems, rotation ages, forest survey methods, and stand management objectives (Du et al. 1996). Results were usually summarized in three categories, a) the growth effect was greater than the mortality effect from the perspective of stand volume yield (Baldwin et al. 2000, Dong et al. 2001, Zhang 2008), b) Conversely, the second study resulted that the mortality effect of thinning was more significant, confirmed separately by Knoebel et al. (1986) on yellow-poplar (*Liriodendron chinense* (Hemsl.) Sarg.), Seiwa et al. (2012) on Japanese conifer (*Cryptomeria japonica* (L. f.) D. Don) and Wyckoff et al. (2014) on red pine (*Pinus koraiensis* Sieb. et Zucc.), c) the growth effect merely offsets the mortality effect, which was agreed by most researchers from varied studying viewpoint. For example, Marquis et al. (1991) believed that thinning the woods, which belong to a small diameter class, had no influence on final stand volume harvest. Lei et al. (2005) found that the stand volume growth rate increased with the increasing of thinning intensity, but there was no significant difference between the total volume yield in the study of mixed stands of *Larix olgensis*, *Abies nephrolepis* and *Picea jazoensis*. Zhang et al. (2006a), Sun et al. (2010) and Xu et al. (2014) proved that the thinning operation had no impact on the yield of stand basal area through comparing with the check and thinned Chinese fir [*Cunninghamia lanceolata* (Lamb.) Hook.] stands; Lindgren held the result that thinning would not affect the crown growth (Lindgren et al. 2013).

Each thinning treatment can result in various harvest numbers in thinned stands, which was studied by many scholars (Xiong et al.1994, Hyytjajnen et al. 2005, Huang et al. 2011). Unfortunately, the growth cycle of forest stand is so long that it usually takes years or even decades to survey stand factors which are used to investigate the influence of thinnings on stand factors. In order to solve this issue, computer technology was phased into simulating forest growth in recent years. Several information systems such as LMS (Landscape Management System) from the United States (McCarter 1997), Heureka system from Sweden (Korosuo et al. 2011), tree growth model simulation system from Wang et al. (1992), thinning visual simulation system from Zhang et al. (2009) and web-based stand visualization system (Guo et al. 2012) have been developed to simulate stand growth. However, only forest visualization simulation of these system researches would be considered, regardless of the influence on stand harvest within different thinning regimes played which contain some factors of when to thin, what number of times to thin, and thinning intensity.

A stand thinning simulation algorithm of timber plantation based on the first thinning age, number of thinning, thinning intensity and interval, and final harvest age was investigated to simulate the thinning effects on stand growth, dynamic model systems, and thinning control regime. A stand volume calculation algorithm based on thinning parameters and an enumeration iterative algorithm were proposed; the corresponding web-based information system was developed. Using the proposed system, we obtained the function of stand volume yield prediction under different thinning schemes and the largest volume yield of Chinese fir; results could support decision-making strategies in forest management.

MATERIALS AND METHODS

Harvest Models and Parameter Constraints

Harvest models: For an even-aged monocultural forest stand, three stand factors that affected the growth of forest harvesting were included, stand age, site index and stand density. In order to study the influence of different thinning parameters, e.g. thinning time, thinning interval, thinning intensity and thinning times, two harvest models, i.e. volume growth models (Equation 1) were selected as the foundation of the studied algorithms (Zhou et al. 2001).

$$M = e^{1.638213+0.12188SI+0.524874\ln N-28.389612/A} \qquad ...(1)$$

Where, M was the stand volume per hectare, SI site index, N number of stems per hectare and A stand age.

Parameter constraints: *Initial stand density*: Stand density is an important factor that affects the forest stand structure. Initial stand density of timber plantation differs among various tree species, stand conditions and timber requirements. The initial stand density of Chinese fir was at 3000 stems/ha to 6000 stems/ha in this study by obtaining the average of stand densities described in previous studies (Xiong 1987, Hong et al. 1997).

***First thinning age*:** Thinnings are introduced to reduce competition between trees. On the choice of the first thinning time, several views were discussed in recent studies. Huang (1994) chose the time at which the current annual increment of stand basal area reached its fastest growth rate as a starting point; Zhang et al. (2011) took the averaged values of the most competitive time and growth stable time of stand crown as the first thinning time; there is also more to what the researchers suggest. Li et al. (2013) chose the time when the canopy density reached 0.9. Forest operators also determined the first thinning time based on experience; for example, conifers in China's southern forest region are first thinned usually in 6 to 10years of growth (Kang 2011).

***Thinning intensity*:** Thinning intensity is measured in terms of percentage and classified according to percentile rank in experimental research in China (Zhang et al. 2005). Thinning intensities were usually divided into 3 categories, i.e. weak thinning intensity (removal ca 15 % -25% of stems), medium (ca 25 % -35%) and heavy (ca 35% -45%).

***Thinning interval and number of thinnings*:** Trees occupy ample growth space to grow faster than typical growth rate after the first thinning is performed. With intensified competition among trees in a few years, stands should be thinned again at a forest canopy density of >0.7 (Kang 2011). Number of thinnings were determined by the final harvest age and thinning intervals. For the fast-growing Chinese fir, the number of thinnings were 1 to 2 times and thinning interval about 5 to 10 years (Xu et al. 2014).

Final harvest cutting age: The final harvest cutting age of a stand varies according to different objectives of forest management. In forest plantation, the proposed principle to determine cutting age is to consider the maturity of economic, quality and quantity (Chen 2010). Determining the final harvest age for timber forest stands can be complex due to various indicators needed to measure the above three types of mature ages. Taking Chinese fir for instance, Chen et al. (2001) pointed out that the rotation of large-diameter timber was about 31-40 years, medium-diameter timber 21-30 years. In our study, the cutting age was set to 21-40 years in this study.

Thinning Simulation Algorithms

Algorithms for calculating volume harvest based on thinning parameters: This algorithm can be used to rapidly calculate the annual stand volume growth before and after the thinnings and the thinned volumes based on the thinning parameters, i.e. initial stand density, site index, the first thinning age, number of thinnings, thinning intervals, thinning intensity and harvest cutting age. The users can adjust thinning parameters empirically to achieve satisfactory thinning strategies. Based on the described parameter constraints, the initial thinning parameters that entered by users are explained in Table 1.

The total yield of stand volume was the sum of the cutting volume and the thinned volume. Stand volume was usually low at the early phase of afforestation, therefore, calculation started from the fifth year and the results are given in Table 2.

Process of the algorithm is shown in Fig. 1. The main steps of the algorithm are as follows:

i. According to the input parameters, a variable *i* was defined and the first thinning time A_1 was read.

Table 1: Explanation of thinning parameters.

Symbol	Range	Description
SI	8-22	Site index
N_0	3000d≤N_0≤6000	Initial stand density and its dimension was N per hectare
k	0≤k	Number of thinnings
j	j=1,2,….	Measurement unit of thinning times
A_j	6≤A_j≤T-5	Thinning age
q_j	15%≤q_j≤45%	Thing intensity
T	21≤T≤40	Harvest cutting age

ii. Compared with *i* and A_1, if *i* is not equal to the first thinning time, then the harvest models which read from the model database directly as Equation 2 (volume model) were calculated by an analytical method. If thinning year was absent, annual volume growth was calculated according to the loop variable *i*, and the corresponding results are given in Table 2.

iii. If *i* is equal to thinning time, the algorithm can be divided into two steps. First, calculate the volume of the i^{th} year and calculate the thinned volume when the thinning time is A_1(Equation 2), which is calculated as follows, with the parameters N_0 (initial plant density), A_1(the first thinning time) and q_1(the thinning intensity at the A_1-th years).

$$M_{thinning1} = f(A_1, N_0, SI) * q_1 \quad ...(2)$$

The stand density reduced from N_0 to N_1 at year A_1, N_1 was calculated as shown in Equation 3.

$$N_1 = N_0 - N_0 * q_1 \quad ...(3)$$

iv. N_0 is replaced with N_1 and the parameters are compared. If the second value of thinning time is obtained, then loop computations are completed according to the second step. If computations are not completed, the third step is repeated, the remaining volume harvest and thinned volume are calculated at A_2^{th} year, and parameters are substituted. At this point, the thinned volume is calculated using Eq. (4) and the results are listed in Table 2 showing A_2 (the second thinning time), N_1 (stand density after the first thinning) and q_2 (the thinning intensity at the A_2^{th} years).

$$M_{thinning2} = f(A_2, N_1, SI) * q_2 \quad ...(4)$$

The stand density decreased from N_1 to N_2 at the moment A_2-th year, N_2 was calculated using Equation 5.

$$N_2 = N_1 - N_1 * q_2 \quad ...(5)$$

These steps are repeated until last thinning time A_j. The amount of thinned volume at this time was calculated using Equation 6.

$$M_{thinningj} = f(A_j, N_{j-1}, SI) * q_j \quad ...(6)$$

v. The volume is calculated in final harvest age (Equation 7), which is denoted as M when the loop variable *i* is larger than the harvest cutting age.

$$M = f(T, N, SI) \quad ...(7)$$

The total volume yield *M* is then calculated using Equation 8, where N_j=N_{j-1}*(1-q_j), and j≥1

$$M_{total} = M + M_{thinning1} + M_{thinning2} + ... + M_{thinningj} =$$
$$f(T, N, SI) + \sum_{j=1}^{k} f(A_j, N_{j-1}, SI) * q_j \quad ...(8)$$

Enumeration iterative algorithm based on the biggest volume yield: This algorithm can be used to calculate stand volume harvest using enumeration and iteration methods within parameter restrictions defined by users and to compare total volume yields in different parameter settings. The thinning strategy that resulted in the highest harvest volume was selected, and subsequently the corresponding number of thinnings, thinning intensity, annual volume harvest and the thinned volume were provided.

The explanation and range of the input parameters in this algorithm are shown as follows:

N_0: initial stand density 3000≤N_0≤6000

k: thinning times 1≤k≤2

T: cutting age 21≤T≤40

The scopes of thinning parameters were required to be set according to the practical situation, based on the parameter constraints in Table 1. For Chinese fir, the time of the first thinning was stipulated to 6 to 10 years and 1 year was set as the incremental unit in the process of enumeration. The thinning intensity was set between 15% and 45%, and increment unit 3%. The reason is that a small intensity increment would lead to minute change for the stand harvest and much computational burden. The thinning interval was set to 5 to 10 years and 1 year as the incremental unit. The final thinning time was A_j, where A_j ≤T-5, and T denoted the cutting age.

Results of annual stand volume are stored in Table 2. The number of thinning strategies were used as table row captions, and the naming rules are as follows: Thinning times - First thinning time - Thinning intensity for the first time-Second thinning time-Thinning intensity for the second time, parameters of each thinning strategy are stored in Table 3.

Algorithm process when thinned once: Enumeration iterative algorithm was based on the number of thinning, e.g. when thinned once, each calculation result was enumerated and the optimal thinning strategy was identified using Bubble Sort within the range of parameter regulation and increment unit. In the algorithm, variable x was defined as thin-

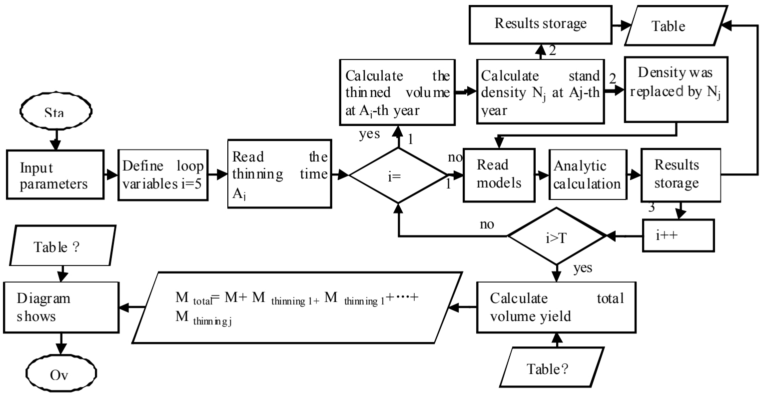

Fig. 1: Proposed algorithm of thinning simulation based on parameters.

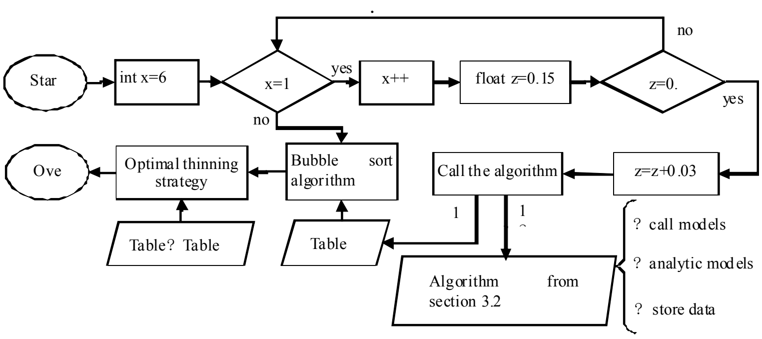

Fig. 2: Process enumeration iterative algorithm when thinning once.

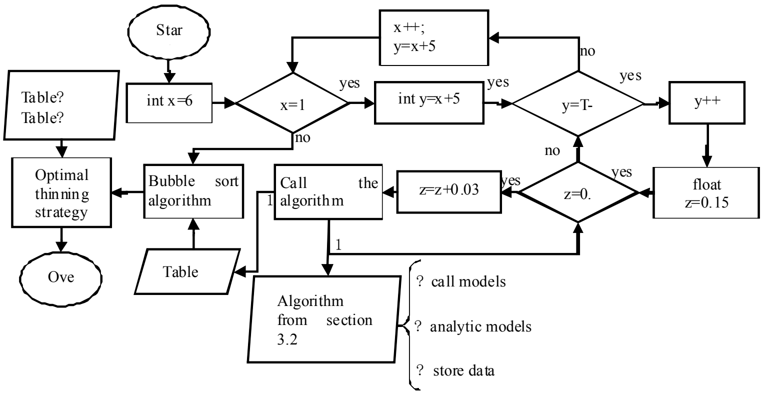

Fig. 3: Process enumeration iterative algorithm when thinning twice.

ning time, variable z was for thinning intensity, and the algorithm process is shown in Fig. 2.

The main steps of the algorithm process are as follows:

i. Thinning started from the sixth year, if x was within 6 to 10 years, x = x+1, and z was given an initial value of 0.15, which represented 15% of thinning intensity.

ii. Thinning intensity variable z was judged whether less than or equal to 0.45, using the algorithm for calculating annual volume harvest based on the thinning parameters (thinning time was the 6th year and thinning intensity was 15%). The calculated data, including annual stand volumes and thinning volume are stored in Table 2 and the thinning strategies are stored in Table 3. At the same time, the value of z was transformed into z + 0.03, that was turned 0.15 into 0.18.

iii. On the premise of the condition, in which thinning time was 6th year, volume yield were calculated respectively, for the thinning intensity were 18%, 21%,..., 45% and the related data are stored in the Table 2 and Table 3.

iv. Calculating volume yield when the thinning time was between 7 to 10 years, the thinning intensity was of 15% - 45%, and making the corresponding data storage.

v. At the end of the two-layers loops, the optimal thinning strategy with the most volume yield would be concluded by using the bubble sort algorithm through total volume harvest values stored in Table 3.

Algorithm process when thinning twice: The first thinning time was defined between 6 and 10 years when thinning was performed twice within the scope of the rules of parameter regulation and enhancing unit. On this basis, the second thinning time was added as 5 years, 6 years... and T-5 years in turn, the range of thinning intensity was still between 15% and 45%. Each calculation result would be enumerated and the optimal thinning strategy could be solved by bubble sort. In variable designs of this algorithm, the integer variables x was for the first thinning time, y was the second thinning time and floating-point variable z was thinning intensity.

Fig. 3 showed the process of the algorithm when thinning twice. The core of thinning twice algorithm was similar to that of thinning once, the difference is that thinning twice algorithm has one more variable, which is y. The main steps of this algorithm are as follows:

i. If the first thinning time was less than or equal to 10 years, then first thinning should start from the 6th year and the second should start from the 6+5=11th year. Each stand volume value was calculated under the thinning intensity was from 15%-45% and storing the data.

Table 2: Storage of calculating result.

Age	5^{th} year	6^{th} years	7^{th} years	…	T^{th} year	Thinning 1	Thinning 2	…	Total harvest
Volume (m^3)	M_5	M_6	M_7	…	M_T	$M_{thinning\ 1}$	$M_{thinning\ 2}$	…	M_{total}

Table 3. Storage of thinning strategies.

No.	Site index	Initial density	Cutting Age	Thinning times	First thinning time	Thinning intensity for the first time	Second thinning time	Thinning intensity for the second time	Total volume harvest
	8-22	N	X_1thyear	1 or 2	X_2^{th}year	%	X_3^{th}year	%	M_{total}

Table 4: Sorting results of enumeration iterative algorithm.

No.	Site index	Initial density	Cutting Age	Thinning times	First thinning time	Thinning intensity for the first time	Second thinning time	Thinning intensity for the second time	Total volume harvest (m^3)
1-10-36	16	4000	30	1	10	36%	-	-	906.74
1-10-39	16	4000	30	1	10	39%	-	-	885.26
…	…	…	…	1	…	…	-	-	…
1-6-45	16	4000	30	1	6	45%	-	-	801.85
2-09-33-21-24	16	4000	30	2	9	33%	21	24%	940.74
2-09-33-22-39	16	4000	30	2	9	33%	22	39%	939.13
…	…	…	…	2	…	…	…	…	…
2-06-45-17-45	16	4000	30	2	6	45%	17	45%	685.70

ii. Similarly, each stand volume yield value, for which the second thinning time was in (6+5)+1, (6+5)+2,... , T-5 years and the thinning intensity was from 15% to 45% was computed separately under the premise of 6^{th} year for the first thinning time and each value would be stored in tables.

iii. Then, separate and repeated calculation was done for the harvest values when the first thinning was in 7, 8, 9 and10 years, the result of the computation was also stored.

iv. At the end of the three-layers loops, the optimal thinning strategy with the most volume yield would be concluded by using the bubble sort algorithm through total volume harvest values stored in Table 3.

RESULTS

Running instance of the algorithms: A plantation thinning simulation decision support system developed by C# programming language and SQL server database, was constructed under B/S structure in this study with the core of volume harvest models and the thinning simulation algorithms. This system fulfilled several functions of parameter input, stand growth and yield predictions, yield curve showing and automatic calculation for the biggest volume harvest.

The proposed algorithms were demonstrated with a practical calculation with a case study of Chinese fir. The input parameters were set as follows:

Initial stand density: 4000 stems/ha

Site index: 16

Cutting age: 30 years

Running instance of the algorithm of calculating volume harvest based on thinning parameters: The case of calculating volume harvest based on thinning parameters needed to input other parameters to the system, for example, the start of 9^{th} year was the first time to thin with 40% of thinning intensity, the second thinning happened in the early time of 18^{th} year with 20% intensity. According to these parameters, the system could compute values of stand annual volume, thinned volume and total volume by the algorithm, the results could be seen in Table 4.

Fig. 4 showed that the stand got 32.35 m^3 of the thinned volume for the first time and 80.97m^3 for the second time, cutting volume (in the 30^{th} year) was 742.53 m^3. Finally, the stand had the volume yield of 855.85m^3 per hectare.

The results were also shown on pages of this system. The input thinning parameters are shown at the left side of the page, there was volume growth curve on the right side and

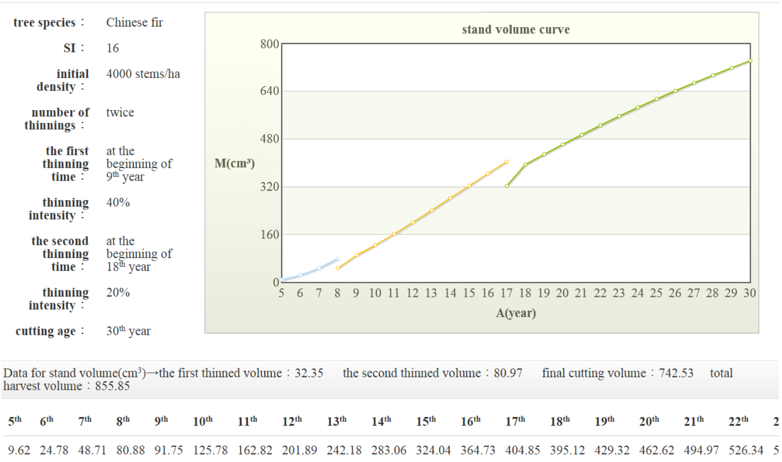

Fig. 4: Stand volume growth simulation based on thinning parameters.

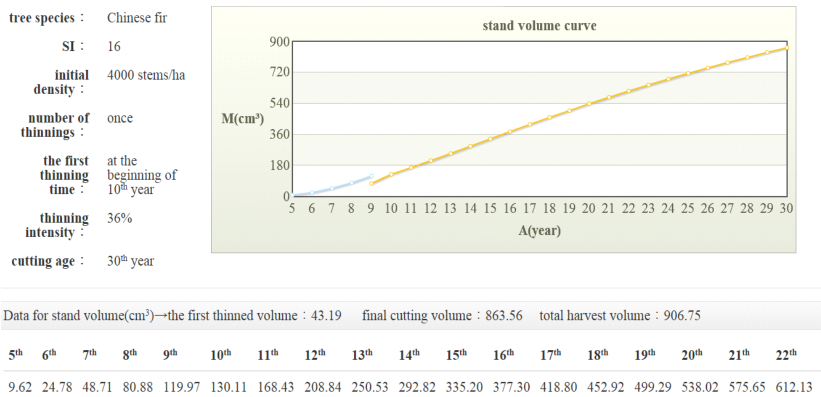

Fig. 5: Running instance of enumeration iterative algorithm when thinning once.

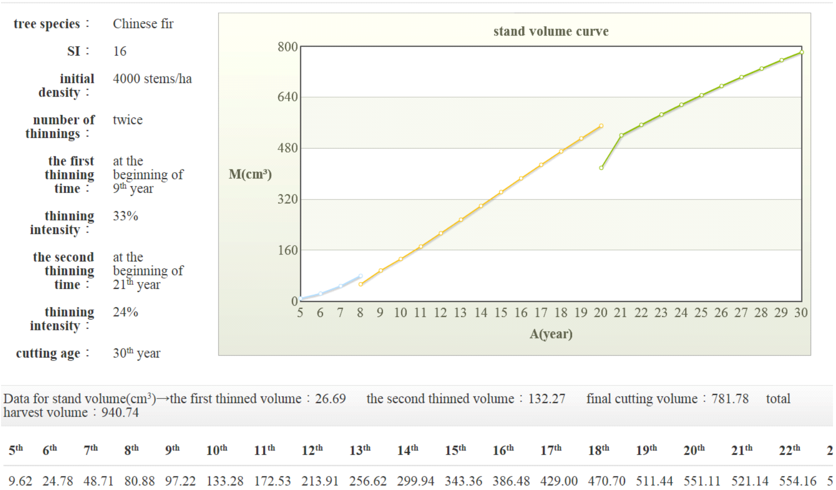

Fig. 6: Running instance of enumeration iterative algorithm when thinning twice.

the corresponding values are presented at the bottom of the page.

Running instance of enumeration iterative algorithm based on the biggest volume yield: The running instance had to choose thinning times in addition to input initial density, site index and cutting age and the system could automatically calculate volume values by enumeration iterative algorithm within the various eligible thinning strategies. Table 4 gives the results of the sorted total volume yield, because of the substantial amount of data and the limited space, only the first four thinning strategies with maximum volume total yield and the minimal strategy have been presented separately when thinning once and thinning twice.

When the stand had been thinned once, the optimal thinning strategy with the biggest volume harvest under the condition of the above parameters showed that the first thinning time was 10th year with 36% of thinning intensity, which could lead to 906.74m^3 per hectare. Second, thinning in 10th year with 39% of thinning intensity, the stand could get 885.26 m^3 per hectare. The strategy was least adopted when the stand had been thinned in 6th year with 45% of intensity, which lead to the smallest harvest.

When thinning twice, the first time to thin was in the 9th year with 33% of thinning intensity, the second thinning happened in 21th year with 24% intensity, under the above condition, the stand of Chinese fir could obtain 940.74 m^3 per hectare which was the biggest volume harvest. When the first and the second thinning time was 9th year and 22th year with 33% and 39% thinning intensity, the stand could get second biggest volume yield, the value was 939.13 m^3 per hectare. With the thinning time for 6th year and 17th year and the thinning intensity of 45%, only 685.70 m^3 per hectare the stand could get.

The best strategy of stand harvest when thinning once and twice with automated enumeration iterative algorithm could be seen respectively in Figs. 5 and 6.

DISCUSSION AND CONCLUSION

At the thinning parameter level, each thinning treatment can result in various harvests. Previous studies indicated that the number of thinning is about 1-3 times. The optimum management schedule included five thinnings on all site indices in the study on Scots pine (*Pinus sylvestris* L.) stands in Spain (Palahí et al., 2003). The Chinese fir plantation was analysed through indicators of volume and outturn percentage for stands with different thinning numbers, and the result was that the growth of stand volume of thinning twice was bigger than thinning once or no thinning (Huang et al. 2011), it is consistent with the conclusions in this study.

For the thinning intensity, Wang (1989) set four sorts of intensity of thinning and finally found that the stand storage of strength intensity (46%) would result to maximum harvests. Dong (2000) considered that thinning intensity by 16% and 25% per plant would achieve the best harvests by using Weibull distribution function in the study on Larch (*Larix gmelinii*) plantation. In Zhang's study, the jack pines (*Pinus banksiana* Lamb.) stands with strong thinning intensity increased 75% volume yields than that without thinning activity in North America, whereas moderate and weak thinning had no effect on the final harvest (Zhang et al. 2006b).

However, few reports about the effects of different thinning time on plantation stands have been conducted. Montero (2001) performed experiments on Scots pine (*Pinus sylvestris*) stands and finally found that setting thinning time in 20-25 years was the best choice in case of good site quality conditions.

In other ways, Hyytjajnen (2005) thought the optimal thinning method can provide benefits except for small trees. Large trees that reach the material requirements are also cut down at the same time to maintain material uniformity of trees in a stand.

In this study, a stand without thinning, would obtain 654 m^3 per hectare through the proposed algorithms, which was lesser than stands which have thinning measures. The first algorithm serves the expectation of managers' aspiration and the second one is more intelligent. Through sorting total volume yields (Table 4), we found that thinning intensity between 33% and 39% could obtain more volume harvest, the first time was primary late and the second thinning time was between 20-23 years. Total yield could be reduced when the thinning intensity was larger or earlier.

In the aspects of harvest models, i) selecting rational harvest models, was the premise of accurate decision making, however, models used in this study have known weakness of ignoring the changes of growth rate after thinning cut. Defects of the models directly led to deviation of the calculation results. However, much time and data would be taken considering the growth rate under the different thinning conditions. Therefore, for the improvement of harvest models further research is still needed. ii) This study stored the models in model database to facilitate users' work to select a better model to replace the existing model. Hence, the algorithms are also applicable to the management decision making for other timber species, if there are rational models.

The optimal thinning treatment for the biggest volume harvest was difficult to get with the calculation based on parameters input of the users but could be quickly and easily obtained by enumeration iterative algorithm. As a result, the users could make adjustments of thinning parameters by the reference for the optimal thinning strategy and using the algorithm on thinning parameters, thus formulating the thinning strategies that took into account the overall interests in the actual forest management.

The restricted range of thinning parameters was based on previous achievements and forest management experiences without considering standard mathematical models. Thinning parameters should be considered as specification of models for future investigations, which could make the results more objective and accurate.

The aim of the algorithms in this paper was to maximize volume yield, in actual forest management, operating costs should be considered. Therefore, further studies should be conducted to combine stand thinning and forestry economic input-output analysis based on current algorithms to maximize economic benefits.

ACKNOWLEDGEMENTS

This study was funded by National Natural Science Foundation of China (Contract No. 31170513). The authors are grateful to Dr. Enying Guo, for technical assistance. The authors would also like to thank the reviewers for their useful comments, which were helpful in improving the manuscript.

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