A THESIS FOR THE DEGREE OF MASTER OF SCIENCE

Profitability Analysis on Sawing *Pinus densiflora* through Log Sawing Simulation

제재 시뮬레이션을 통한 소나무 원목의 제재 수익성 분석

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ABSTRACT

This study conducted a profitability analysis on sawing *Pinus densiflora* logs by comparing the profitability of lumber and pulp-chip productions. In order to estimate the maximum value recovery from log sawing, a log sawing simulation model was developed based on dynamic programming algorithm proposed by Reinders and Hendriks (1989). Through the log sawing simulation, *Pinus densiflora* logs in lengths of 3.6 m and 2.7 m were optimally sawn for maximized lumber value in regards with the dimensions and prices of lumber products in Korea. On the other hand, 1.8 m *Pinus densiflora* logs were applied for pulp-chip production considering the current timber harvesting and log allocation in Korea. Net profits generated from the two productions were estimated using the data obtained from the actual sawmills and pulp-chip manufacture facilities. According to the result, sawing *Pinus densiflora* logs for 3.6 m and 2.7 m lumber products generated 861% and 723% higher net profits, respectively than pulp-chip production with 1.8 m logs. Between the two lumber productions, the average net profit generated from sawing 3.6 m logs was 24% higher than sawing 2.7 m logs.

In addition to the comparative analysis on sawing profitability, the sawing potential of short (1.8 m) *Pinus densiflora* logs was also evaluated for wooden cutting board and wooden tray manufacture using the log sawing simulation model. The lumber for wooden cutting board manufacture could be sawn from the log with 18 cm of diameter and the lumber for wooden tray manufacture from the log with 22 cm of diameter.

The results of this study reconfirm that sawlog harvesting would lead to higher timber sale profits and support the bucking decisions in terms of value recovery and increased stumpage value of *Pinus densiflora* stands in Korea. Additionally, the study also suggests that thorough considerations of various end-uses of harvested timber would increase the timber sale profits.

Keywords: lumber production, log sawing, sawing profitability, bucking length, sawing optimization

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Ⅰ. INTRODUCTION

In the process of converting a tree into raw materials for wood products, a tree is firstly felled, delimbed and bucked into logs with certain lengths considering its end-uses such as poles, lumber products, pulp-chips, etc. Although many decisions are made in each process, bucking decision is the one that holds the key to potential timber sale profits (Faaland and Briggs 1984) because, depending on the decision, a tree is transformed into different wood products with various values. For example, pulp-sticks are considered low quality timber because they are used as raw materials for pulp-chip manufacture, which is traded for low prices. On the other hand, sawlogs or veneer logs are considered high quality timber because they are used in lumber or furniture manufacture, which has far higher premium than pulp-chips.

In Korea, during the past few decades, much of the trees, even with large diameter at breast height (DBH) have been bucked into pulp-sticks (1.8 m in length). The simple bucking pattern without considerations of end-uses has resulted in loss of potential profits in timber sale and consequently underestimated the stumpage value of Korea's forestland (Seol, Han et al. 2016).

The value of *Pinus densiflora*, which covers 64% of the entire forest area in Korea (Korea Forest Service 2016) has also been underestimated by the current bucking problem. In the past, with its mechanical and chemical characteristics similar to Douglas fir (*Pseudotsuga menziesii*) and Western Hemlock (Tsuga heterophylla), and its symbolic characteristics to people in Korea, it had been widely used as high quality sawlogs for *Hanok* structures, Korean traditional furniture, and other wood products such as cutting boards, bowls, utensils, etc. (Korea Forest Research Institute 2011). However, even with its premium as a sawlog, the pine trees have been bucked into mainly pulp-sticks generating far less timber sale profits.

In terms of bucking a tree into sawlogs, the bucking decisions have to be associated with the value recovery of lumber sawn from the logs. In other words, a cut has to be made on a tree where maximized lumber value can be obtained (Bobrowski 1994). Thus, the optimal sawing patterns that maximize the value recovery from a log has to be suggested first in order to finally determine the bucking decisions.

Much effort has been made to solve the complex problem. In the early studies including Pnevmaticos and Mann (1972), Briggs (1980), Faaland and Briggs (1984), Lembersky and Chi (1984), Rogler (1984), Maness and Adams (1991), mathematical models that predict the volume and the value recovery from log bucking were developed in order to determine the optimal bucking patterns for maximized profit. Especially, the models developed by Faaland and Briggs (1984), and Maness and Adams (1991) integrated log sawing algorithms into optimization of log bucking patterns.

Later, with the advanced computerization and industrial technology, those mathematical models were applied to various automated systems or equipment such as timber harvesters or automated sawing machines (Rönnqvist 2003).

On the other hand, in Korea, limited number of studies analyzed value recovery from log sawing based on the volume yield from sawn logs (Kwon 2003, Kwon, Kim et al. 2007, Kwon, Han et al. 2013). However, the models developed by them were volume-oriented, which do not necessarily lead to maximum value recovery of lumber.

In order to support bucking decisions for maximized value recovery from *Pinus densiflora* timber, this study conducted a comparative analysis on sawing profitability of the pine logs in different lengths in association with their end-uses. In addition, sawing potential of short pine logs was also evaluated for product diversification.

Ⅱ. OBJECTIVES

The overall objective of this study were to analyze sawing profitability of *Pinus densiflora* logs in different lengths (3.6 m, 2.7 m, and 1.8 m) in association with their end-uses and evaluate sawing potential of short *Pinus densiflora* logs.

The specific objectives were to

- develop a log sawing simulation model
- analyze sawing and chipping profitability of *Pinus densiflora* logs
- evaluate sawing potential of short *Pinus densiflora* logs for small wood products

Ⅲ. LITERATURE REVIEW

Since 1960's, in need of maximum use of raw materials, simulation models that optimize sawing patterns or log breakdown for maximized lumber recovery have been developed.

Some of the earliest models are based on mathematical algorithms. Peter and Bamping (1962) applied diagrams of bucked logs for best sawing pattern. Hallock (1962) mathematically analyzed the effect of saw kerf and lumber sizing on lumber yield. Taylor and Garton (1970) applied a transparent overlay procedure to analyze the effect of cant size and log diameter on lumber yield. McAdoo (1969) developed a computer simulation model that mathematically predicts lumber yield from small logs. Hallock's theoretical model was also developed into a computer simulation program by Hallock and Lewis (1971). The program called BOF (Best Opening Face) determines the best opening face of a given log that maximizes lumber recovery by iterative enumerations. However, the earlier simulation models had limitations that they tended to overestimate lumber yield because the logs were assumed cylindrical (though BOF was later modified to assume logs as truncated cones). Thus, simulation models that consider log shape more realistically have been developed. Richards (1977) developed a log sawing simulation model based on truncated cone to analyze the effect of log shape on lumber yield. Airth and Calvert (1973), Pnevmaticos and Mouland (1978), Adkins, Richards et al. (1980) and Savsar and Kersavage (1982) also applied truncated cones to their log sawing simulations.

Later on, with the rapid advance in computer graphics, 3D visualization was implemented in simulation models to accurately represent log geometry. Garcia (1987) developed a visual sawing simulator called SEESAW, which considers not only the 3D representation of a given log but also internal defects on a pruned log. Todoroki (1990) developed a computer sawing simulation system called AUTOSAW, which defines and analyzes the sawlog resources. The system, unlike other simulation models goes through three independent programs, AUTOSET, AUTOSAW, and SAWNOUT, which provide sawing patterns and sawing strategies, sawing simulations, and analysis of the result of the sawing simulations, respectively.

Thereafter, many other log sawing or log breakdown simulation models based on 3D representation of log geometry have been developed and evolved with new technologies such as X-ray, computer tomograph (CT), nuclear magnetic resonance (NMR), ultrasound or gamma rays (Grundberg and Gronlund 1997) and applied to wood manufacture industry for maximized value recovery.

Meanwhile, dynamic programming (DP), one of the optimization methods has also been applied to the log sawing problems as determining optimum sawing patterns, in mathematical terms, is a two- or multi-dimensional cutting stock problem (Geerts 1984). DP proposed by Bellman (1954) is as stated above an optimization method that decomposes a complex problem into simpler subproblems called stages which contain states. The optimization procedure goes through every state in each stage recursively until the overall optimum is found. Although linear programming (LP), and simulation and heuristic methods have also been applied to log breakdown problems, DP has advantages in computational speed and quality of the optimal solution (Todoroki and Rönnqvist 1997, Puumalainen 1998). In the case of LP, the linear format of equations and parameters makes the size of the LP problem enormous to compute while DP allowing flexible formulations reduces number of alternatives handled, which in turn shortens the computation time (Puumalainen 1998). In comparison with simulation and heuristic approaches where the global optimum is not guaranteed, DP generates high quality optimal solutions due to its optimizing characteristics (Todoroki and Rönnqvist 1997). With its nature of dividing a problem and adaptability to problems requiring a sequence of interrelated decisions, DP has been applied to the log breakdown problems (Briggs 1980, Rönnqvist 2003).

Geerts (1984) developed a nested two-dimensional DP algorithm that decomposes log breakdown into two different levels. The first level cuts a log into flitches placing the cut-line on the x-axis of the cross section of the log. In the second level, the cuts are made perpendicular to the y-axis cutting a flitch into lumber products.

Faaland and Briggs (1984) integrated bucking and log sawing processes. Their DP model composed with three levels bucks a tree into logs, saws the logs into flitches, and the flitches are cut into lumber products. Reinders and Hendriks (1989) also developed three-dimensional DP algorithm, which optimizes bucking and log sawing decisions.

In Korea, on the other hand, (Kwon 2003, Kwon, Kim et al. 2007) developed a lumber yield estimation model for *Pinus koraiensis*, *Larix kaempferi*, and *Quercus acutissima* based on tree shape analysis. In recent years, Kwon, Han et al. (2013) developed a lumber and residue yield estimation model for *Larix kaempferi*. Other studies include a merchantability analysis on *Robinia pseudoacacia* and *Alnus* species (Lee, Chung et al. 1985, Lee, Chung et al. 1986), lumber yield estimation from *Pinus densiflora, Pinus koraiensis* and *Larix kaempferi* using a portable sawing machine (Lee, Kwon et al. 1989).

This study adapted DP algorithm proposed by Reinders and Hendriks (1989) to develop a log sawing simulation model in order to generate optimal sawing patterns and estimate the maximum value recovery from log sawing.

Ⅳ. RESEARCH FRAMEWORK

Figure 1 shows the framework of this study. Firstly, a log sawing simulation model was developed based on literature review and data collection from sawmills in Korea. With the simulation model, *Pinus densiflora* logs in lengths of 3.6 m and 2.7 m were optimally sawn for maximized value recovery. Pulp-chip production was estimated with the data obtained from pulp-chip manufacture facilities. The net profits generated from the two types of wood products were than compared. In addition to the profitability comparison, short (1.8 m) logs of *Pinus densiflora* were also simulated sawn for lumber products for small wood products manufacture based on their dimensions obtained from the wood products manufacturers. The lumber recovery was then analyzed to evaluate the sawing potential of the short logs.

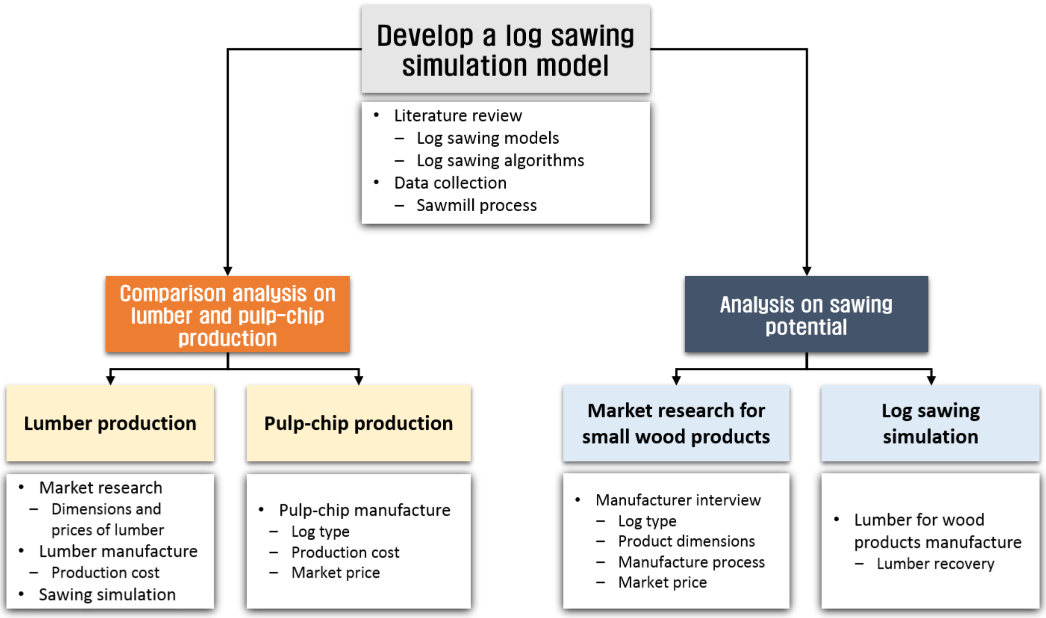

Figure 1. Research framework

Ⅴ. MATERIALS AND METHODS

1. A log sawing simulation model

1) Model assumptions

Since this study aims to compare the profitability of sawing and chipping *Pinus densiflora* logs in different lengths, it was assumed that logs were already bucked into either sawlogs (3.6 m or 2.7 m) or pulp-sticks (1.8 m). Additionally, the shape of a log was assumed cylindrical with small end diameter being on both ends of the log.

Band-sawing is the most widely used sawing type in lumber manufacture industry in Korea. With this sawing type, a log goes through a two-step breakdown process to be transformed into lumber products. A log is firstly broken down into flitches and the flitches broken down into lumber products (Figure 2). Since the cuts of band-sawing are made perpendicular to *x*-axis, it was assumed that a log is rotated 90˚ after cuts are made for flitches. This, in other words, means that cuts made perpendicular to *x*-axis break down a log into flitches (*x*-level) and the next cuts made perpendicular to *y*-axis break down the flitches into lumber products (*y*-level). Thus, the breakdown of a log was analyzed on the two-dimensional grid.

In terms of cutting pattern, this sawing type (band-sawing) only generates guillotine cuts (Figure 3) where a cut is made in between two edges of opposite side of a cross section of a log.

Thus, a log sawing simulation model was developed based on the two-step log breakdown process (*x* and *y*-level) with guillotine cutting patterns.

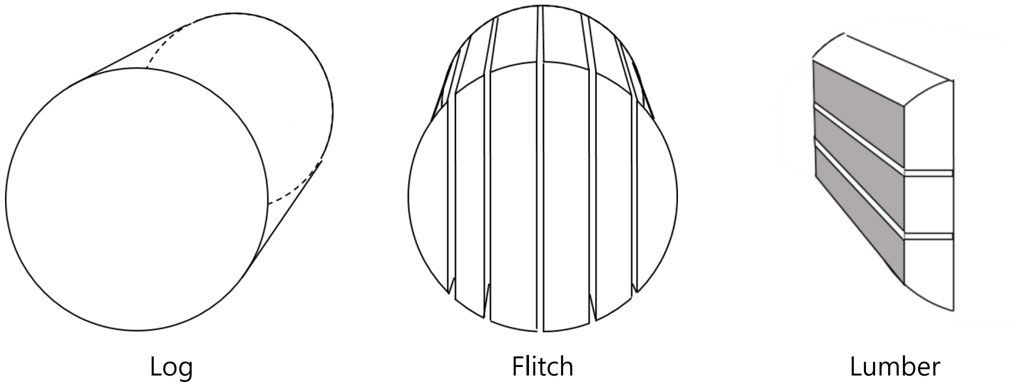

Figure 2. Log breakdown process

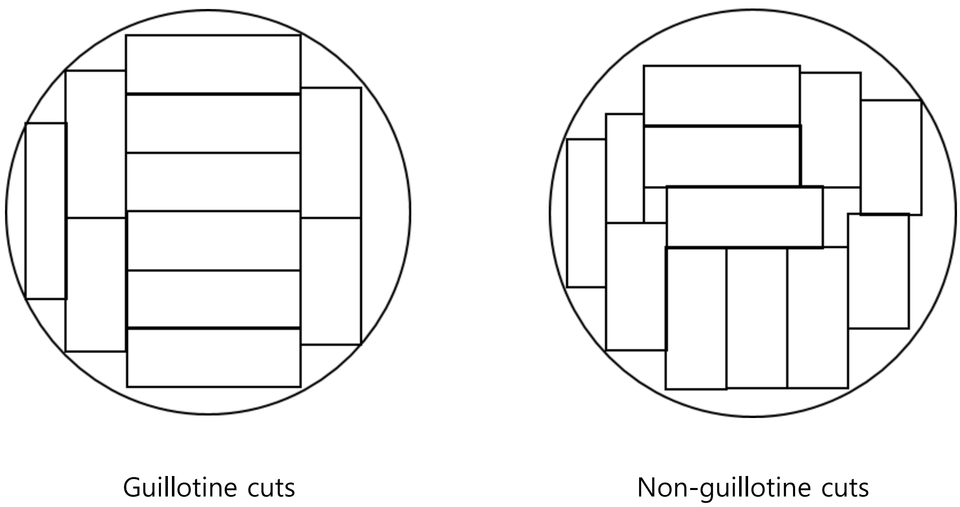

Figure 3. An example of guillotine cuts

2) Structure of the model

Figure 4 shows the process of finding the optimal sawing pattern for maximized log value. Based on the two-step log breakdown process explained above, the model firstly cuts a log into flitches in a way that the log value is maximized based on the flitch values. In this step, the log value is sum of the values of flitches cut from it. The flitch value is determined in the next step where each flitch is cut into lumber products. Here, the flitch value is sum of the values of lumber products cut from it. Thus, the two processes: (1) flitch cut and (2) lumber cut interact with each other to generate the optimal sawing pattern for maximized log value based on the maximized lumber and flitch values.

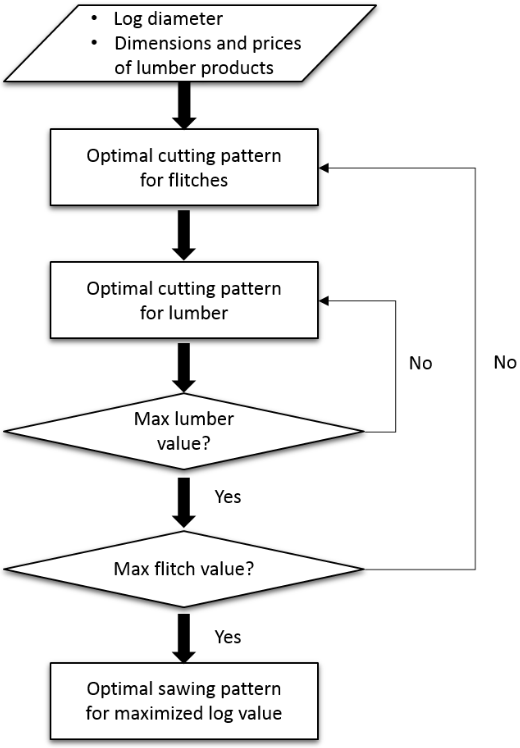

Figure 4. Model flow chart

3) Mathematical algorithm

Dynamic programming decomposes a complex problem into smaller subproblems that interact with each other as a whole to solve the complex problem (Bellman 1957). In this case, the problem of finding an optimum sawing pattern for a given log based on dimensions and prices of lumber products is decomposed into two subproblems as the log breakdown process includes two steps (*x* and *y*-level).

This study adapted DP algorithm developed by Reinders and Hendriks (1989). The algorithm is originally based on three-dimensional space where log length, width and height of the circular cross section of a log are considered. However, only the width and height of the cross section of the log were considered in this study because logs were assumed to be bucked into certain length classes for comparison purposes. Thus, two-dimensional DP algorithm was finally applied in this study.

x-level

Let x be the point on the *x*-axis where a cut is made on the circular cross section of a log and ϕ_x be the width of the flitch starting from the point x. Then, the decision to be made in the *x*-level is the width (ϕ_x) of the flitch that maximizes the value $XF(x)$. Considering the circular cross section of the log, a decision is made on every point on the *x*-axis from the very left (x^{a}) to the very right (x^{ϖ}) of the width of the cross section (Figure 5).

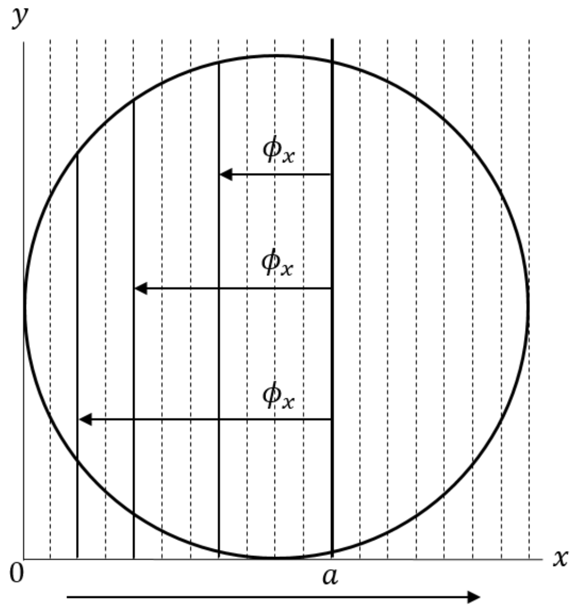

Figure 5. Diagram of possible decisions on width when $x = a$

The value of the flitch cut in between x and ϕ_x, $G(x, \phi_x)$ is then determined in the next level by the value of lumber products, $YF_x(y)$ cut from it. If optimum decisions were made at all the previous points on *x*-axis, the solution, $XF(x - \phi_x)$ is stored. Thus, DP algorithm for *x*-level can be formulated as follows:

$$XF(x) = \max\{G(x, \phi_x) + XF(x - \phi_x)\}$$

$$x^a \leq x \leq x^\omega,$$

$$\phi_x \leq x,$$

$$G(x, \phi_x) = YF_x(y)$$

y-level

In y-level, the objective function is to maximize the value of lumber products ($YF_x(y)$) cut from the flitch. The decision to be made here is the height of the cross section of the log (ϕ_y) starting from the point y on the y-axis (Figure 6).

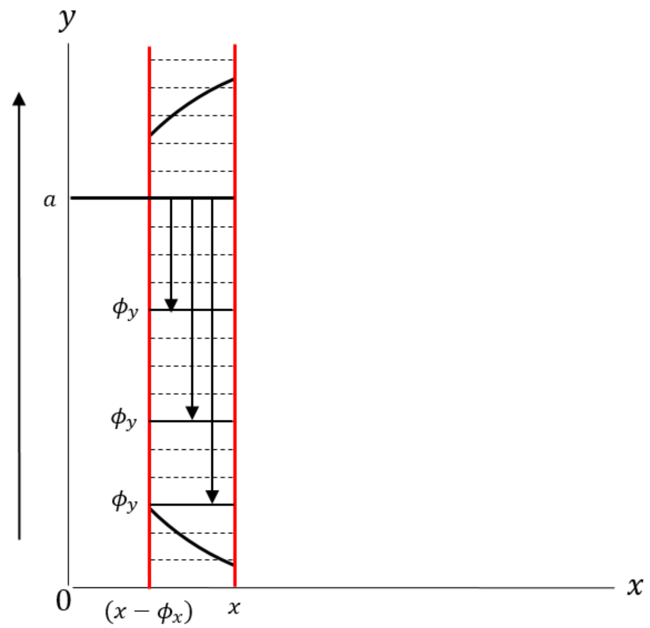

Figure 6. Diagram of possible decisions on height when $y = a$

In other words, the type of lumber product (n) with a value of (v) to be cut, either rotated (90°) or not from the flitch is determined. y, in this case, ranges from the very bottom of the circular cross section of the log (y_β) where y = 0 to the effective height of the flitch (y_γ), which is determined by the function of the flitch width in x-level (ϕ_x). The decision on the type of lumber product (n) and whether to rotate the product or not is determined by the value of the lumber products $v(n)$ cut from the flitch. If optimum decisions were made at all the previous points on y-axis, the solution $YF_x(y - \phi_y)$ is stored. Thus, DP algorithm for

y-level can be formulated as follows:

$$YF_x(y) = \max\{H(y, \phi_y) + YF_x(y - \phi_y)\}$$

$$y_\beta(\phi_x) \leq y \leq y_\gamma(\phi_x),$$

$$\phi_y \leq y,$$

$$H(y, \phi_y) = v(n)$$

The optimization is then processed through using the output of y-level, the value of lumber, $YF_x(y)$ as input to x-level to determine the optimal width of a flitch, ϕ_x and backtracking the decisions at each level until the optimal solution is found.

The mathematical algorithm was then programmed using Python 3.6 and run on Intel® Core™ i7-3770 CPU @ 3.40 GHz.

2. Comparative analysis on sawing and chipping profitability of *Pinus densiflora* logs

1) Analysis on sawing profitability of *Pinus densiflora*

(1) Process of profitability analysis using the log sawing simulation model

In order to conduct a sawing profitability analysis, data regarding log types and lumber products were obtained first. The obtained data (log dimensions, lumber products, and lumber prices) were then applied to the log sawing simulation model to generate optimal sawing patterns for the maximum value. With the information provided by the simulation model (type of lumber product, the number of each type of product produced), profitability analysis was conducted.

Figure 7 shows the process of analyzing the profitability of lumber production followed by detailed explanations on each process.

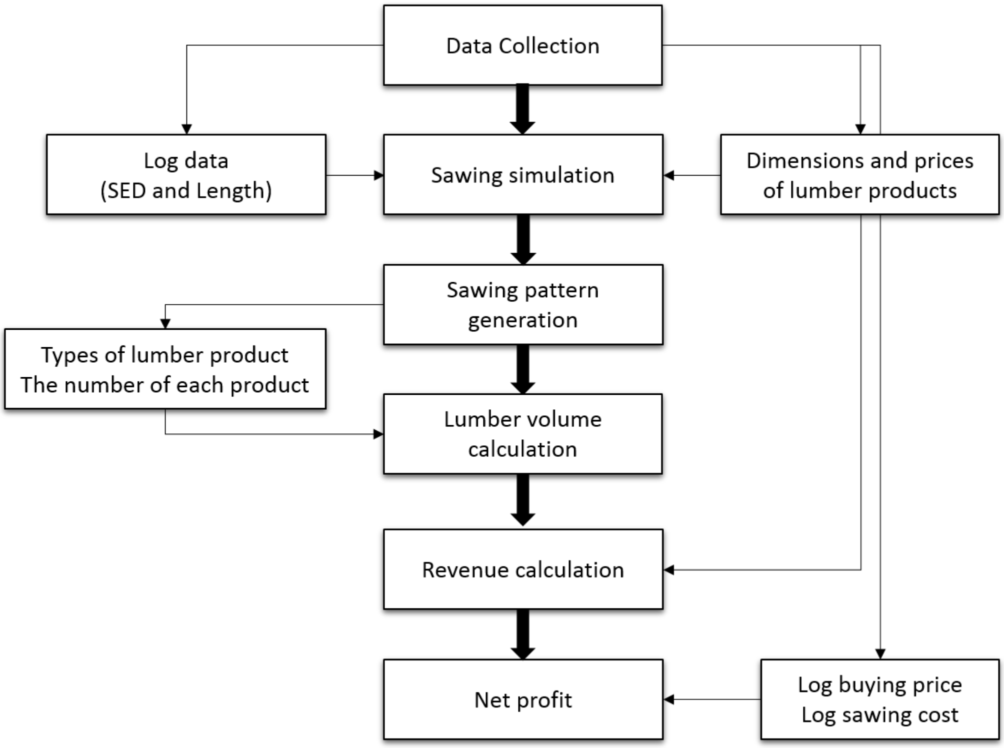

Figure 7. Process of log sawing profitability analysis

(2) Data collection

① Lumber products and prices

In order to simulate sawing *Pinus densiflora* logs for lumber production, dimensions and prices of lumber products that are currently traded in the domestic market were obtained from National Forestry Cooperative Federation in Korea. There are two length types (3.6 m and 2.7 m) with various dimensions that are traded in the market. 3.6 m types contain 10 different products including two board type products (type 1 and 2) where width is at least three times longer than thickness. On the other hand, 2.7 m types contain 13 different products including five board type products. Table 1 shows the dimensions and price of each lumber product in detail.

Table 1. Dimensions and prices of lumber products (National Forestry Cooperative Federation, 2016)

Type	Lumber products (3.6 m)		Lumber products (2.7 m)	
	Dimensions (mm)	Price (₩)	Dimensions (mm)	Price (₩)
1	27 × 89	8,600	27 × 89	6,500
2	38 × 38	5,500	38 × 38	4,200
3	38 × 89	13,200	38 × 89	9,900
4	38 × 140	18,900	38 × 140	14,200
5	89 × 89	29,700	38 × 184	20,700
6	140 × 140	6,800	38 × 235	31,200
7	150 × 150	45,500	38 × 285	38,300
8	180 × 180	115,000	90 × 90	21,400
9	200 × 200	155,000	90 × 140	35,700
10	250 × 250	250,000	140 × 140	51,000
11	-	-	180 × 180	86,300
12	-	-	200 × 200	116,300
13	-	-	250 × 250	187,500

② **Lumber production cost**

In general wood manufacturing businesses, total production cost is comprised with various cost functions depending on production process such as receiving, log sorting, debarking, sawing and edging, drying, etc. (Korpunen, Mochan et al. 2010). However, for the purpose of this study, log buying price and log sawing cost (debarking + sawing + edging) were considered for lumber production cost.

Log sawing cost was obtained from seven sawmills (three in Incheon, two in Gangwon-province, and two in Gyonggi-province) producing lumber products in Korea. They provided their average sawing cost for producing 1 m^3 of lumber. The cost varied from ₩50,000/m^3 to ₩70,000/m^3, but in this study, the average cost of ₩60,000/m^3 was applied.

In terms of log buying price, 'The quarterly Market Prices of Domestic Timber' published by KOFPI in 2016 was reviewed. The publication provides log prices of different species based on their log grading system. The prices of *Pinus densiflora* logs based on the grades are shown in Table 2.

Table 2. Market prices of *Pinus densiflora* logs by grade (Korea Forestry Promotion Institute 2016)

	Supreme	1st	2nd	3rd	Bolt	Pulp
SED (cm)	>42	>27	>21	>18	>12	>6
Length (m)	>2.1	>3.6	>3.6	>2.1	>2.4	>1.8
Price (₩/m^3)	417,800	229,100	195,200	177,700	172,400	62,200

*SED: Small end diameter

(3) Profitability Analysis

The profitability analysis was conducted with 3.6 m and 2.7 m logs with diameter classes ranged from 6 cm to 40 cm in consideration of the two length groups of lumber products (Table 1). The volume of each log was obtained from the log volume table (Korea Forest Research Institute 2011).

Step 1. Log sawing simulation

As mentioned above, two log types (3.6 m and 2.7 m) with diameter classes ranged from 6 cm to 40 cm were optimally sawn for the maximum profit with the dimensions and prices of lumber products (Table 1) obtained through market research.

Step 2. Optimal sawing pattern generation

Through the simulation, the optimal sawing pattern was generated for maximized log value. Additionally, types of lumber products sawn and the number of each product type were also computed through the simulation model.

Step 3. Estimation of the volume of sawn lumber

The volume of each product type sawn is calculated by multiplying the number of each product type sawn and the volume of each product type. Since the log sawing simulation model only generates two-dimensional results, lumber length, in this case, log length is also multiplied in the volume calculation.

In addition to the volume estimation, recovery rate of lumber yield was also calculated by dividing the total lumber volume by the volume of the log.

Step 4. Revenue generated from lumber production

Revenue generated from sawing a log is calculated by multiplying the volume of each product type sawn and the price of each product type.

Step 5. Net profit of lumber production

Net profit of log sawing is calculated by subtracting the revenue by the total lumber production cost, which includes log-buying price and sawing cost. For the calculation of log buying price, the volume of each log was multiplied by market price according to their dimensional grades (Table 2). In terms of sawing cost, ₩60,000/m^3 obtained from seven sawmills was applied.

2) Profitability Analysis on pulp-chip production with *Pinus densiflora*

(1) Process of Profitability Analysis on pulp-chip production

Figure 8 shows the process of analyzing the profitability of pulp-chip production. Data regarding pulp-chip production and pulp-chip price were obtained as well as log types used for pulp-chip manufacture. Based on the information obtained, the volume of pulp-chip produced from a log and the net profit of pulp-chip production were calculated. Detailed explanations are as follows.

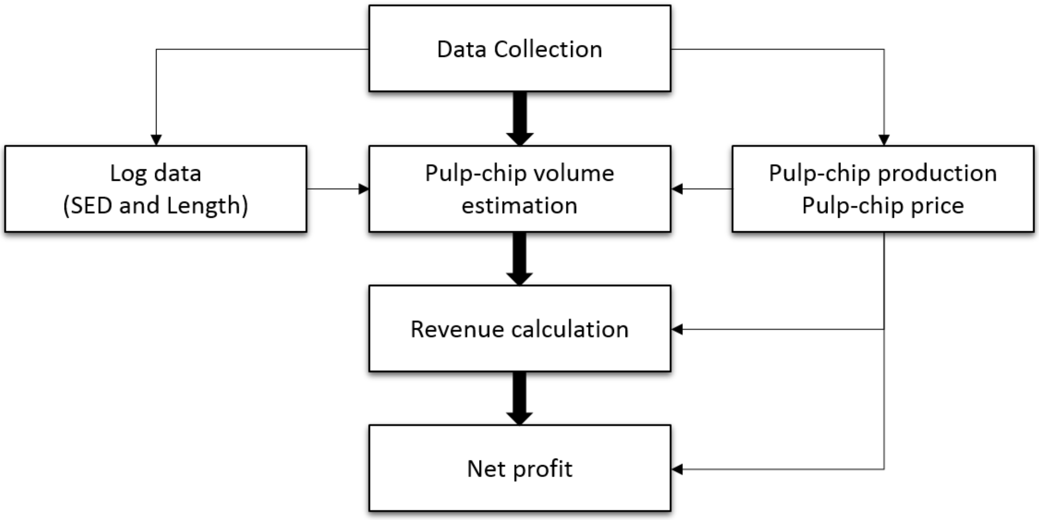

Figure 8. Process of analysis on the profitability of pulp-chip production

(2) Data Collection

① **Pulp-chip production cost**

Information regarding pulp-chip production and raw material use was obtained from three wood-chipping facilities (one in Gangwon-province and two in Gyeongbuk-province).

Pulp-chips are manufactured through the process of debarking and chipping. Since wood fibers are used for pulp manufacture, bark portion is first removed by debarking process and the heartwood of the log is chipped for pulp-chips. Thus, both debarking and chipping processes were included in chipping cost and the cost of ₩16,000/m^3 obtained from the facilities was applied in this study.

Meanwhile, the production yield of pulp-chip manufacture was 2.5 m^3 of pulp-chips from 1 ton of logs according to the three facilities.

In terms of log buying price, since all logs less than or equal to 1.8 m long are considered as pulp-sticks according to the log grading system in Korea, (Table 2), ₩62,200/m^3 was applied regardless of their diameter class.

② **Pulp-chip market price**

Based on the information provided by the three facilities, pulp-chips are traded in volume (m^3) rather than weight (ton). It is because depending on weather conditions (dry or wet), moisture content of pulp-chips may vary.

The average market price of pulp-chip 1m^3 was also obtained from the facilities and the price of ₩65,000/m^3 was applied in this study.

(3) Profitability Analysis

Unlike the lumber production scenario, logs in 1.8m long were applied to the profitability analysis considering the length of pulp-stick logs in Korea. However, the same diameter classes (6 cm-40 cm) were applied for comparison purposes. The volume of each log was obtained from the log volume table published by (Korea Forest Research Institute 2011) as same as the lumber production scenario.

Step 1. Pulp-chip volume estimation

Since 1 ton of logs yields 2.5 m^3 of pulp-chips, the volume of pulp-chips produced by a log was calculated by multiplying the weight of a log and the yield rate of 2.5m^3/ton. In order to estimate the weight of a log, the green weight equation was used.

$$\text{Green weight of a log(ton)} = \text{Moisture content} \times \text{Dry weight (ton)} \times \text{Log volume } (m^3)$$

The moisture content and dry weight of *Pinus densiflora* (1.15 and 0.44 respectively) were obtained from Wood Science (Jung 1998). The volume of each log applied in this analysis was as mentioned above, obtained from the log scaling table (Korea Forest Research Institute 2011).

Step 2. Revenue calculation

Revenue generated from pulp-chip production was calculated by multiplying the volume of pulp-chips produced from a log and the market price.

Step 3. Net profit calculation

Net profit was calculated by subtracting the revenue by the total pulp-chip production cost, which includes log-buying price, and chipping cost.

3. Analysis on sawing potential of short *Pinus densiflora* timber for wood product manufacture

1) Research Process

Figure 9 shows the process of analysis on sawing potential of short *Pinus densiflora* logs. In order to simulate lumber productivity of 1.8 m *Pinus densiflora* logs for small wood product manufacture, information regarding the small wood products were obtained through manufacturer interview and market research. Dimensions of small wood products were then applied to the log sawing simulation model. Then, the productivity analysis was conducted with the information generated from the simulation.

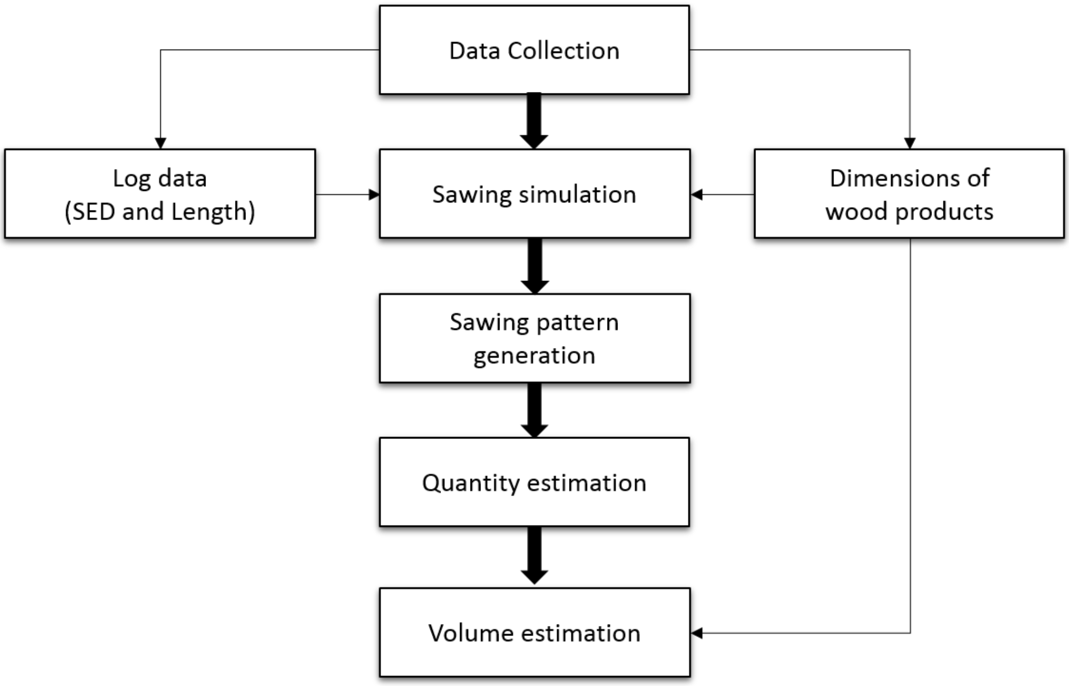

Figure 9. Process of analysis on sawing potential of short *Pinus densiflora* logs for small wood products

2) Data Collection

In order to analyze the sawing productivity of 1.8 m *Pinus densiflora* logs, seven wood products manufacturers in Korea (four wooden cutting board manufacturers and three wooden tray manufacturers) were interviewed for their production process, product dimensions, and raw materials used.

(1) Log type

According to the interview with the manufacturers, both types of manufacturers use short *Pinus densiflora* logs regardless of their sweep or crook. Since the final products (wooden cutting board or wooden tray) are small, curvature of a log can be compromised.

(2) Production process

In terms of production process as shown in Figure 10, first, lumber is sawn from a log based on dimensions (thickness × width) of wood products. Then the sawn lumber is cut into pieces and secondary processing is applied to final manufacture.

① ② ③ ④

Figure 10. Manufacture process of small wood products (cutting board and wooden bowl)

3) Analysis on sawing potential

(1) Log Sawing Simulation

Considering that both types of manufacturers (wooden cutting board and wooden tray) use short logs for wood product manufacture, 1.8 m of *Pinus densiflora* logs with diameter class ranged from 6 cm to 40 cm were applied to the log sawing simulation model.

Production of each lumber type (lumber for wooden cutting boards and for wooden tray) was then simulated separately in order to compare the productivity. One type of each wood product that is mainly manufactured by the seven manufacturers was selected for the purpose of this study. Thus, dimensions of 40 × 180 × 210 mm and 30 × 120 × 255 mm were applied to the log sawing simulation model for wooden cutting board and wooden tray, respectively.

(2) Estimation of lumber production

Through the simulation, number of lumber products for wood product manufacture was generated. Since only one type of each wood product was considered in this study, the volume of total lumber produced was calculated by multiplying the number of lumber produced and the volume of a single lumber product. Additionally, since the simulation model generated only two-dimensional results; thickness and width of a lumber, log length, in this case, 1.8 m was also multiplied to the volume calculation.

In addition to the volume estimation, recovery rate of lumber production was also estimated by dividing the total lumber volume by the log volume.

Ⅵ. RESULTS AND DISCUSSION

1. Optimal sawing pattern for 3.6 m *Pinus densiflora* logs

Table 3 shows the result of sawing simulation on 3.6 m *Pinus densiflora* logs for maximized profit. Types of lumber product and the number of each lumber type produced by the simulation are shown in the table by diameter class (6 cm-40 cm).

Lumber product(s) were produced from all diameter classes (6 cm–40 cm) and the lumber production increased in number of products and product types as diameter class increased. However, small products such as type 1, 2, and 3 were produced mostly even from logs with large diameters. Even though larger products with higher price were expected to be produced as diameter class increased, it was evident that producing small products in large number would yield more profit.

The most production was found in diameter class 38 cm as 36 products of type 1, 2, and 3, while the most product types (five lumber types) were produced from the log with diameter of 40 cm.

Table 3. Number of lumber products produced from 3.6 m *Pinus densiflora* logs by product type and small diameter

No.	Dimensions	SED (cm)																	
		6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40
1	27 × 89	-	-	-	-	2	1	3	-	-	2	6	-	-	2	2	-	1	1
2	38 × 38	1	1	2	4	1	2	-	3	3	6	6	8	7	5	5	2	16	10
3	38 × 89	-	-	-	-	1	2	3	5	7	6	5	6	13	-	15	3	19	12
4	38 × 140	-	-	-	-	-	-	-	-	-	-	-	-	-	2	-	1	-	1
5	89 × 89	-	-	-	-	-	-	-	-	-	-	-	2	-	-	1	-	-	5
6	140 × 140	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
7	150 × 150	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
8	180 × 180	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
9	200 × 200	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
10	250 × 250	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total lumber production		1	1	2	4	4	5	6	8	10	14	17	16	20	9	23	6	36	29

*SED: Small end diameter

2. Optimal sawing pattern for 2.7 m *Pinus densiflora* logs

Table 4 shows the result of sawing simulation on 2.7 m *Pinus densiflora* logs for maximized profit. Types of lumber products and the number of each lumber type produced are shown in the table by diameter class (6 cm-40 cm).

Like the case of sawing 3.6 m *Pinus densiflora* logs, all diameter classes from 6 cm to 40 cm produced lumber product(s) and the production increased in number and types as diameter class increased. In addition, large lumber products were not produced even from large diameter classes. However, board type products such as type 5, 6, and 7 that are relatively large in size were included in the optimal sawing pattern as diameter class increased. The board type lumber is more beneficial than large (type 10-13) and small lumber products (type 1-3) in volume recovery and in profitability because of its small thickness and higher price, respectively.

The most production was found in diameter class 40 cm as 20 products of type 1, 2, 3, 6 and 7, while the most product types (five lumber types) were produced from diameter class of 26, 36, 38, and 40 cm.

Table 4. Number of lumber products produced from 2.7 m *Pinus densiflora* logs by product type and small diameter

No.	Dimensions	SED (cm)																	
		6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40
1	27 × 89	-	-	-	-	2	1	3	-	-	-	1	2	6	-	2	2	-	2
2	38 × 38	1	1	2	4	1	2	-	3	3	12	4	1	-	7	4	7	7	8
3	38 × 89	-	-	-	-	1	2	3	3	7	2	2	-	-	1	-	-	1	2
4	38 × 140	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-
5	38 × 184	-	-	-	-	-	-	-	1	-	-	1	2	-	-	-	2	-	-
6	38 × 235	-	-	-	-	-	-	-	-	-	1	2	3	2	3	2	1	3	4
7	38 × 285	-	-	-	-	-	-	-	-	-	-	-	-	2	2	4	4	4	4
8	90 × 90	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
9	90 × 140	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
10	140 × 140	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
11	180 × 180	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
12	200 × 200	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
13	250 × 250	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total number of products		1	1	2	4	4	5	6	7	10	15	10	8	10	13	12	16	16	20

* SED: Small end diameter

3. Lumber yield and recovery rate of sawing 3.6 m and 2.7 m *Pinus densiflora* logs

Both sawing cases showed a gradual increase in lumber volume as diameter class increased as shown in Figure 11. The volume of 3.6 m lumber products increased from 0.006 m^3 at diameter of 6 cm to 0.389 m^3 at diameter of 40 cm and the volume of 2.7 m lumber products increased from 0.004 m^3 to 0.276 m^3.

In terms of recovery rate, higher recovery rate was evident in 3.6 m lumber production for every diameter class. The average recovery rate of 3.6 m lumber production was 56% with the lowest of 25% at diameter of 8 cm and the highest of 68% at diameter of 40 cm. In the case of 2.7 m lumber production, the average was 52% with the lowest of 23% at diameter of 8 cm and the highest of 64% at 40 cm. Even though higher recovery rate was expected from 2.7 m log sawing at first because of more various product types, 3.6 m lumber production showed higher recovery rate at every diameter class (6-40 cm) showing that producing smaller products in large number (3.6 m lumber production) generates higher recovery rate.

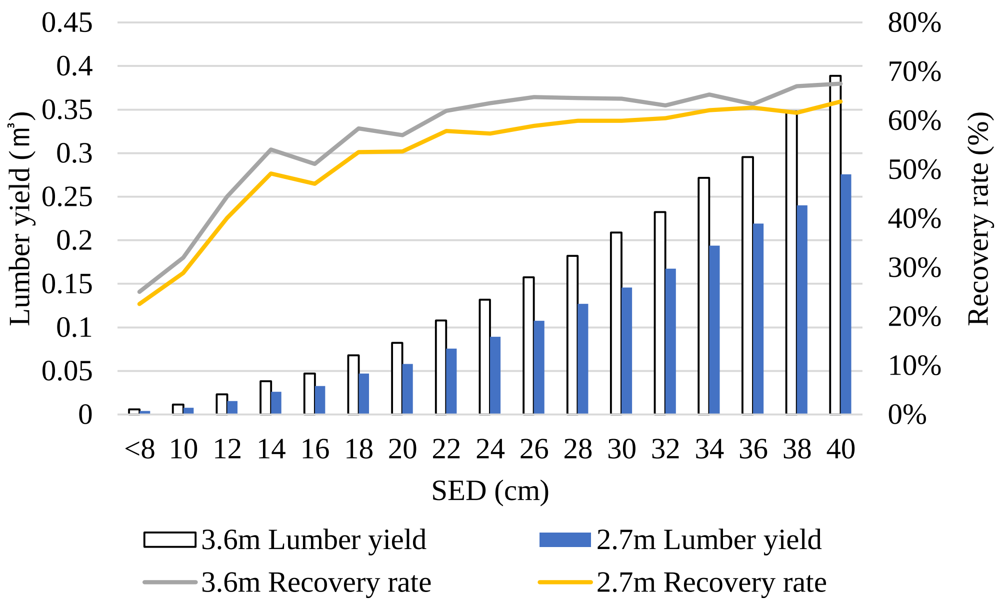

Figure 11. Volume yield and recovery rate of 3.6 m and 2.7 m lumber production

4. Pulp-chip yield from chipping 1.8 m *Pinus densiflora* logs

Table 5 shows the result of pulp-chip production with 1.8 m *Pinus densiflora* logs. As shown in the table, the volume of pulp-chip production gradually increased from 0.015 m^3 to 0.681 m^3 as diameter class increased. Since the production was estimated assuming that 1 ton of log yields 2.5 m^3 of pulp-chip, the recovery rate was the same as 237% in every diameter class.

Table 5. Pulp-chip yield from a given log weight

SED (cm)	Green weight of a log (ton)	Pulp-chip yield (m^3)
6	0.006	0.015
8	0.011	0.027
10	0.017	0.043
12	0.025	0.061
14	0.033	0.083
16	0.044	0.109
18	0.055	0.138
20	0.068	0.170
22	0.082	0.206
24	0.098	0.245
26	0.115	0.288
28	0.133	0.334
30	0.153	0.383
32	0.174	0.436
34	0.197	0.492
36	0.221	0.552
38	0.246	0.615
40	0.272	0.681

* SED: Small end diameter

5. Net profit comparison between lumber production and pulp-chip production

Table 6 shows the result of profitability analysis of lumber production using 3.6 m and 2.7 m *Pinus densiflora* logs and of pulp-chip production using 1.8 m *Pinus densiflora* logs.

According to the result, net profits generated from both lumber production cases were higher than pulp-chip production in every diameter class. The average net profit of sawing 3.6 m log was 861% and sawing 2.7 m log was 723% higher than chipping 1.8 m logs (Figure 12).

Between the lumber production cases, sawing 3.6 m log showed higher profitability in every diameter class. The average net profit of 3.6 m lumber production was 24% higher than 2.7 m lumber production.

Table 6. Net profit comparison between lumber and pulp-chip production with *Pinus densiflora* logs

SED (cm)	Net profit of lumber production (₩)		Net profit of pulp-chip production (₩)
	Log length 3.6 m	Log length 2.7 m	Log length 1.8 m
<8	1,911	1,527	866
10	5,233	4,125	1,355
12	13,314	10,379	1,950
14	23,656	18,081	2,657
16	30,170	23,004	3,470
18	44,527	33,788	4,389
20	56,839	43,970	5,420
22	72,458	54,883	6,556
24	85,822	69,304	7,806
26	99,274	88,363	9,161
28	123,132	108,170	10,621
30	141,844	127,466	12,195
32	157,936	151,908	13,873
34	182,008	180,093	15,665
36	218,712	194,871	17,562
38	233,988	218,832	19,564
40	263,544	253,546	21,679

*SED: Small end diameter

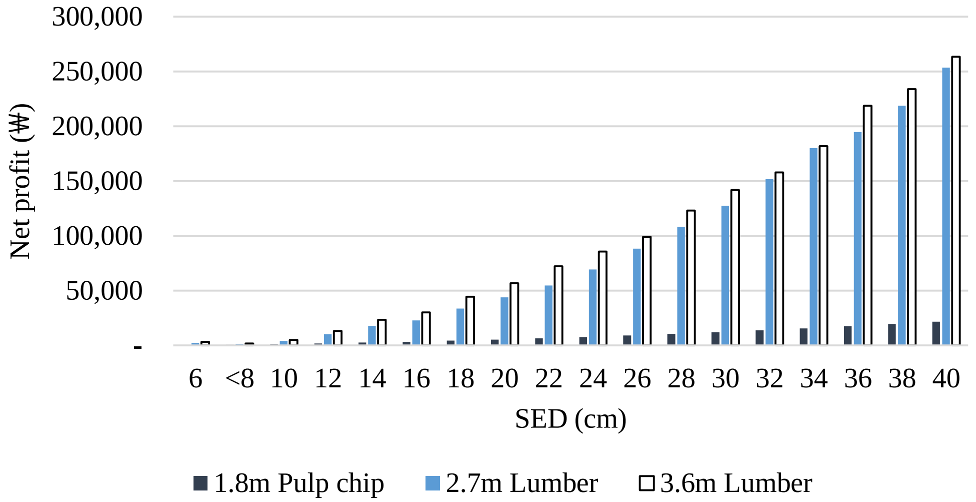

Figure 12. Net profit generated from the two lumber production cases and net profit generated from the pulp-chip production

6. Production estimation of lumber for wooden cutting board

Figure 13 shows the result of log sawing simulation of 1.8 m *Pinus densiflora* logs for wooden cutting board lumber. According to the simulation result, lumber (40 × 180 × 1800 mm) for wooden cutting board manufacture was produced from a log 18 cm in diameter. The number of the lumber production increased from two to twelve as diameter class increased.

In terms of recovery rate, the highest recovery rate was found in between diameter class 32 cm and 36 cm as 56%. The lowest recovery rate was 37% at diameter of 24 cm. However, unlike the previous lumber production cases (3.6 m and 2.7 m lumber production), the recovery rate fluctuated in between diameter classes. Especially, the level of fluctuation was higher in relatively small diameter classes (18 cm-24 cm). The fluctuation can be explained by the same lumber production with the increase of diameter class.

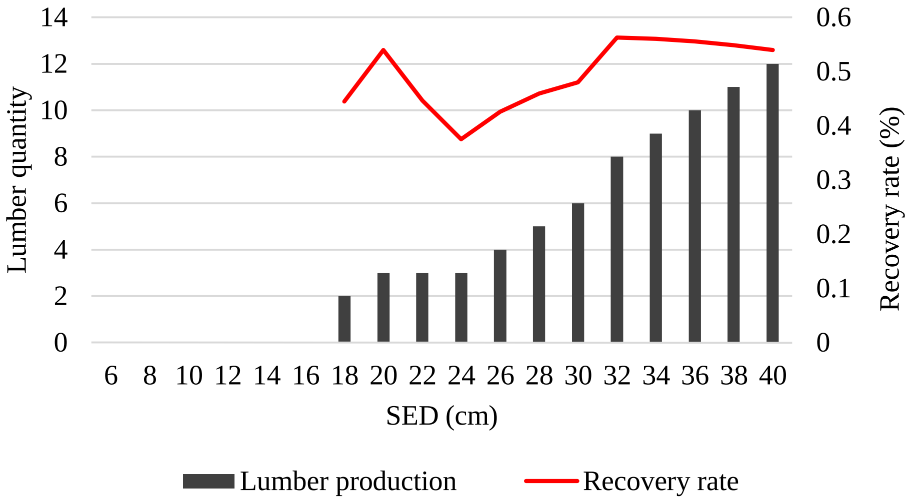

Figure 13. Number and recovery rate of lumber production for wooden cutting board manufacture

7. Production estimation of lumber for wooden tray

The result of log sawing simulation of 1.8 m *Pinus densiflora* logs for wooden bowl is shown in Figure 14. According to the simulation result, lumber (30 × 120 × 1800 mm) for wooden tray manufacture was produced from a log with diameter of 22 cm and the lumber production increased as diameter class increased.

In terms of recovery rate, similar with the case of the dimension lumber production, it showed a gradual increase as diameter class increased. The highest recovery rate was 59% at diameter 40 cm and the lowest was found at diameter of 22 cm.

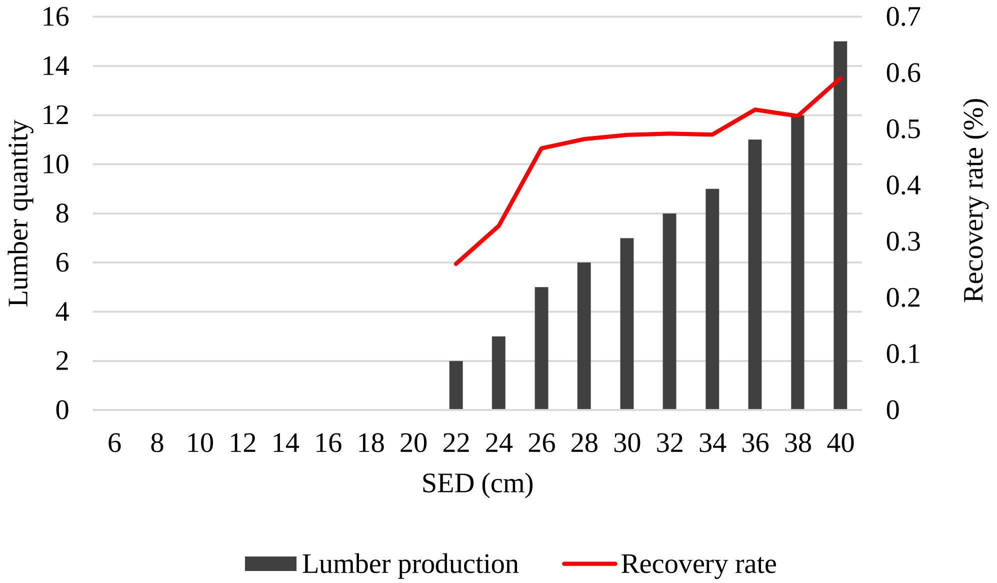

Figure 14. Number and recovery rate of lumber production for wooden tray manufacture

Ⅶ. CONCLUSION

This study analyzed the value of *Pinus densiflora* logs by comparing profitability of lumber production and pulp-chip production with logs in different lengths. In order to estimate the maximum value recovery generated from log sawing, a log sawing simulation model was developed first. The model was based on DP algorithm proposed by Reinders and Hendriks (1989). Since this study assumed that logs had been already bucked into certain lengths, two-dimensional DP algorithm, which breaks down a log into flitches and the flitches into lumber products, was applied.

Using the sawing simulation model, 3.6 m and 2.7 m logs were sawmilled for 3.6 m and 2.7 m lumber products, respectively. 1.8 m logs were debarked and chipped for pulp-chip production. The profitability of the three cases were then analyzed for comparison purposes.

According to the results, sawing the longest log, 3.6 m logs, generated the highest net profit among the three cases. The second highest net profit was generated from sawing logs 2.7 m long, which was the second longest log length of the three lengths of log types applied in this study. The difference of the net profit between the two lumber sawing cases (3.6 m and 2.7 m) were 24% in average. However, the net profit of both lumber sawing cases was 861% and 723% higher than pulp-chip production with 1.8 m logs. Additionally, when considering by-products such as wood slab and sawdust produced from log sawing, the profitability of sawing *Pinus densiflora* logs will be higher.

In addition to the comparative analysis on sawing profitability, the sawing potential of short (1.8 m) *Pinus densiflora* logs was also evaluated for wooden cutting board and wooden tray manufacture using the log sawing simulation model. According to the result, lumber for wooden cutting board manufacture (40 × 180 × 1800 mm) can be obtained from a log with diameter of 18 cm and lumber for wooden tray manufacture (30 × 120 × 1800 mm) from a log with diameter of 22 cm. The number of the lumber production for both wood products showed a gradual increase as diameter class increased.

The result of this study addresses two important suggestions on the current timber harvesting method and timber sale. First, decisions on bucking patterns have to be in association with timber sale profits. In other words, log buckers who determine where to locate a cut on a harvested tree should consider the end-uses of bucked logs because depending on the location of the cut, the value of each log changes enormously. Second, even if poor bucking patterns have been made in the first place, various end-uses of the bucked log have to be considered in the process of log allocation in order to increase timber sale profits.

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국문 초록

본 연구에서는 국내산 소나무 원목을 활용한 제재목 생산과 펄프칩 생산의 수익성을 비교분석 하였다. 먼저, 원목 제재를 통한 최대 수익을 산출하기 위하여, Reinders와 Hendriks(1989)가 개발한 동적계획법 알고리즘을 기반으로 원목 제재 시뮬레이션 모델을 개발하였다. 또한, 국내에서 유통되고 있는 제재목의 규격과 가격을 바탕으로 3.6m와 2.7m 재장의 소나무 원목에 대한 제재 시뮬레이션을 수행하였다. 펄프칩 생산의 경우, 현재 원료재로 유통되고 있는 1.8m 재장의 소나무 원목을 적용하여 생산성을 분석하였다. 각 생산 시나리오에서 발생하는 순수익은 국내 제재소 및 펄프칩 생산업체에서 수집한 현장 데이터를 바탕으로 산출하였다. 연구 결과, 3.6m와 2.7m 재장의 소나무 원목을 활용한 제재목 생산 순수익의 경우, 1.8m 재장의 소나무 원목을 활용한 펄프칩 생산의 순수익보다 각각 861%와 723% 더 높은 것으로 나타났다. 재장별 소나무 원목의 제재 수익성을 분석한 결과, 재장이 더 긴 3.6m 소나무 원목의 제재 순수익이 2.7m 원목의 제재 순수익보다 24% 높은 것으로 나타났다.

소나무 원목의 제재 수익성 분석과 더불어, 소나무 단목(1.8m)의 제재 상품성을 평가하기 위하여, 도마 및 함지박 가공용 판재에 대한 제재 시뮬레이션을 수행하였다. 시뮬레이션에 적용된 각 목재제품의 생산방식 및 규격에 대한 정보는 가공업체 인터뷰를 통하여 수집되었다. 시뮬레이션 분석 결과, 도마 가공용 판재의 경우, 1.8m 소나무 원목의 말구직경 18cm에서부터 생산이 가능한 것으로 나타났고, 말구직경 22cm에서부터 함지박 가공용 판재를 생산할 수 있는 것으로 나타났다.

본 연구의 결과는 제재목 생산을 위한 장재 생산이 벌채 수익 면에서 우위에 있다는 것을 확인하고 우리나라 소나무 임분의 가치 증진을 위한 조재작업 의사결정에 기여할 것으로 판단된다. 또한 목재소품 원자재로써의 부가가치가 높은

소나무 단목의 경우, 다양한 용도 고찰을 통하여 매각 수익성을 높일 수 있을 것으로 사료된다.

주요어 : 제재목 생산, 원목 제재, 제재 수익성, 조재 길이, 원목 제재 최적화

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