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Multiple-criteria stem bucking (*Picea abies* L. Karst.) for maximizing monetary value of timber trade

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Abstract— *In this study, timber trade scenarios are considered in a wood procurement region of Finland. This multiple objective decision-making situation includes the timber purchase from forest owners and the lumber sales from sawmill to abroad. The situation is further complicated by a number of stem bucking instructions of sawmill during different periods. In practice, this decision problem has been solved by applying single-objective stem bucking instructions in harvesters. Due to the complex nature of the problem, single-objective solution can't be directly used to support the timber trade in a manner that it is techno-economically relevant to the forest owners and industries. In this study, stand parameters and timber trade attributes were measured in local wood procurement conditions to improving the bucking instructions. Three scenarios of how the simulation system works based on the real stem diameters and optional monetary value of logs are investigated in the timber-trade process. The Finnish timber trade market is subjected to agreements regarding stem bucking regulations. These agreements could be made on the basis of the three criteria suggested in this study accounting for the effects of stand classification on the timber sales of forest owners and the lumber sales of export companies.*
Keywords**— *cut-to-length method, forest industry, forest owner, multi-criteria analysis, stem bucking, wood procurement.***

I. INTRODUCTION

In Finland, the average annual timber trade of industrial softwood logs has been 23 million m^3 (sob) during recent years of which the share of Norway spruce (*Picea abies* L. Karst.) logs cuttings were 54% (Forest wood removals by forestry centre 2017). In the current wood procurement logistics, the cut-to-length method with stand's harvesting instructions are used for managing the timber trade process in a manner that wood procurement of forest industry is acceptable to forest owners (Palander 1998, Palander et al. 2009). On the one side of the wood procurement process, stands can be harvested into favorable log dimensions (log assortment) to sawmill. In this customer-driven process, the sawmill customer has market information about the demand of lumber markets for constructing of a target distribution of logs. On the other hand, stand's harvesting instructions of the forest industry are subject to the available wood supply of timber trade markets (Palander et al. 2009). Therefore, the target distribution must consider various agreements of different timber trades and preferences of forest owners in the markets (Figure 1).

In forest stands, harvester's computer optimizes several bucking alternatives for each stem by taking into account stand's bucking instructions for the harvester operator, which include the price matrix, target distribution and the various other bucking guidelines. The operator can use the bucking proposals displayed by the harvester computer (i.e. automatically bucking) at the harvesting site. The harvester operator can also utilize manual bucking to cut damaged or defected parts of log stems (Kärhä et al. 2017). If the manual bucking is used, the operator decides the crosscutting point of logs without the bucking proposals displayed by the automatically bucking system. In this respect, the harvester operator can consider local wood procurement conditions for improving the bucking outcome. By the other words, the operator can subjectively adjust the bucking solution to better solve the combinatorial complexity of the timber trade.

In addition to the consideration of different log assortments, the quality of stem of Norway spruce (Picea abies L. Karst.) does not vary significantly, and correspondingly the monetary value changes are small in different lumber grades. If the value of lumber of Scots pine (Pinus sylvestris L.) is considered, it is more dependent on the quality of stem. For consideration of the

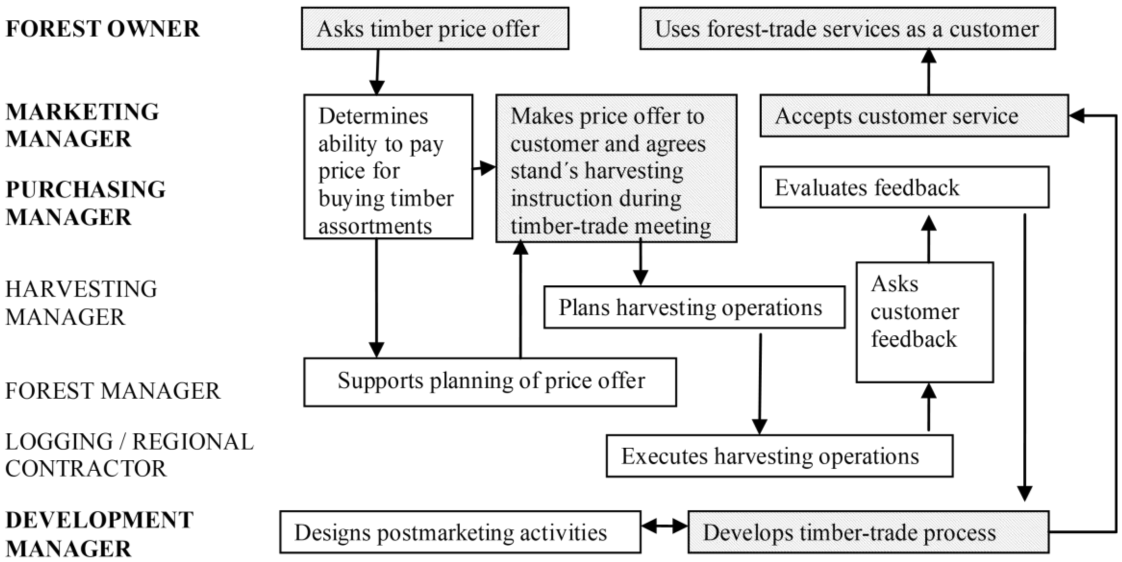

Fig.1: Wood supply of timber-trade markets in Finland (Palander et al. 2009).

quality aspect, the harvester operator can utilize manual (quality) bucking on the pine stem. However, several research groups have studied stem bucking and suggested that the benefits of computer-aided bucking are larger than the benefits of manual bucking (Wang et al. 2004, 2009, Akay et al. 2010, 2015, Serin et al. 2010). So, computer-aided bucking of stems does not significantly decrease the quality of lumber. After harvesting, the goodness of bucking outcome can be evaluated with several attributes, for instance by using the log percentage or apportionment degree (Malinen and Palander 2004).

In the study by Kärhä et al. (2016), the harvester operators were asked when they use manual bucking? The results revealed that more than a half (55%) of the harvester operators regarded automatic bucking as significantly better than manual bucking to produce the best bucking outcome with spruce log stems. In the study, the log percentage received the highest weight as the criterion for goodness of bucking outcome, which are used by forest owners (Figure 2) (Kärhä et al. 2017). Its relative weight was, on average, 29%. Furthermore, the operators raised the apportionment degree, the log reject percentage and the production value of logs as the important criteria for evaluation of bucking outcome, which are used by a mill customer. The relative weights of these criteria were 20–25%, which were at very similar levels with both spruce and pine stems. In the study of Kärhä et al. (2017), the variation of opinions among the harvester operators was

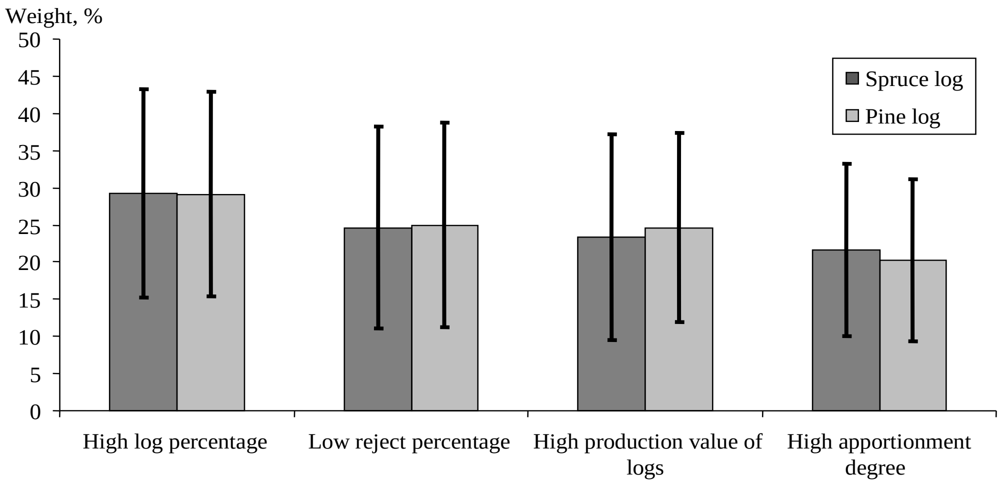

Fig.2: The weights of the criteria for the good bucking outcome in cutting log stands. The bars describe the average opinion of harvester operators and the black lines the standard deviation (Kärhä et al., 2016).

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large between the statements, which indicate different preferences of interest groups.
In the 2000s, the multi-criteria based methods were implemented in participatory decision support of wood procurement in Finland. For example, Palander (1998) aggregated the preferences of various interest groups over feasible sets of wood procurement alternatives using multi-criteria methods. This wood procurement planning approach was later specified at the timber harvesting management level (Laukkanen et al. 2004), but in the timber-trade management (Figure 1) the multi-criteria approach is a new issue. In this study, the purpose is to examine its applicability in the actual timber trade decision-making situation, in which the ultimate goal is assumed to be the maximization of monetary value.

In Finland, stem bucking is managed conventionally. Same systems have been applied during decades (Näsberg 1985, Bergstrand 1990, 1994, Möller and von Essen 1997, Malinen and Palander 2004, Kivinen et al. 2005), while computers and information networks have been developed largely without any limits for more efficient systems. It is reasonable to ask; could it be beneficial to use different bucking instructions, if average volumes of stems in stand removal are for instance 450 and 900 dm3? It has been shown that the apportionment degree of stem bucking varies depending on the size of trees, because small-sized trees have fewer bucking alternatives than large trees (Bergstrand 1994). Actually, group of stands could be systematically classified using parameters of local forest information that describe stand and trees: location/geography, site class, age, cutting method, shares of tree species, the average volume of stems in stand removal, average diameter of stems in stand removal, average length of stems in stand removal, quality (e.g. butt rot, branches). Figure 3 depicts an example for the stand classification based on the local forest information about the average diameter of stems in stand removals.

So far, no studies have been accomplished on the effects of using multiple criteria for construction of bucking instructions of softwood (i.e. Norway spruce) stands in the timber trade decision-making situation. This could be made by applying the stand classification in timber-trade simulations. Therefore, we undertook a study on:
- The accuracy of forest information on the stand classification,
- The effects of stand classification and monetary value classification on the bucking outcome,
- The relationship of criteria for the maximization of monetary value of timber trade, e.g., the log percentage (%), value of stand (€) and relative production value of logs (€/m^3).

The hypothesis of our study was: In respect to the timber trade, the best bucking outcome is achieved for the timber sales of forest owners and the lumber sales of export companies, when the bucking instructions of stands are subject to the multiple criteria and stand classification.

II. MATERIAL AND METHODS

The stem bucking and cutting production files of 11 Ponsse forest harvesters was collected from July 2013 to June 2014 at the stands of Stora Enso Wood Supply Finland. There were totally 216 harvesting sites (stands, *n*) in eastern Finland. The data collection was done at the beginning of August 2014. The total volume of softwood log section of stem data was 60,000 m^3, which varied from

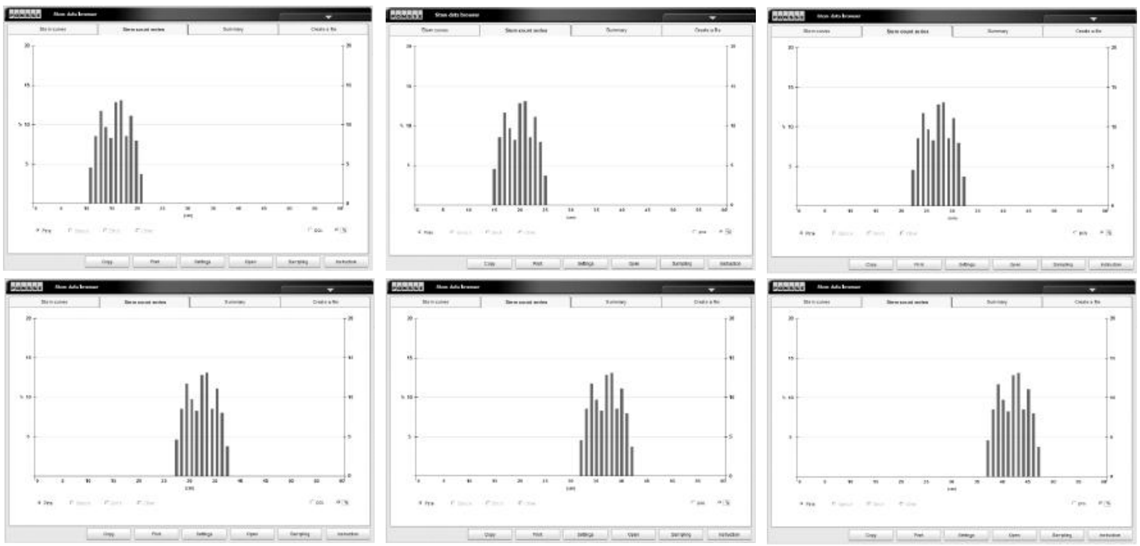

Fig.3: Six stand classes which depict differences between average frequency distributions of stem diameter (1.3 m) in stand removal.

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Table.1: Target distributions of stem bucking in timber trade simulations.

Wood procurement period 2013-14	Reference	Stand classification Scenario 1 (predicted)	Scenario 2 (harvester)	Scenario 3 (implicit)
1.7 – 2.9.2013	Target distribution 1	Three target distributions for stand classification (7,8,9)	Three target distributions for stand classification (7,8,9)	Target distribution (6)
3.9 – 17.9.	Target distribution 2			
18.9 – 7.10.	Target distribution 3			
8.10 – 20.10.	Target distribution 4			
21.10 – 1.1.	Target distribution 5			
2.1 – 30.6.2014	Target distribution 6			

Table.2: Price matrices of stem bucking in timber trade simulations.

Wood procurement period 2013-14	Reference	Stand classification Scenario 1 (predicted)	Scenario 2 (harvester)	Scenario 3 (implicit)
1.7 – 2.9.2013	Price matrix 1	Three price matrices for stand classification (5,6,7)	Three price matrices for stand classification (5,6,7)	Logs' monetary values of sawmill (8)
3.9 – 17.9.	Price matrix 2			
18.9 – 7.10.	Price matrix 2			
8.10 – 20.10.	Price matrix 3			
21.10 – 1.1.	Price matrix 3			
2.1 – 30.6.2014	Price matrix 4			

1,848 to 12,897 m^3 per harvester in the study. In addition to the harvesters' stem data, the data from sawmill's production system and company's forest information system were collected. There were six bucking instruction files in production during the study periods: 1.7.2013–2.9.2013, 3.9.2013–17.9.2013, 18.9.2013–7.10.2013, 8.10.2013–20.10.2013, 21.10.2013–1.1.2014, 2.1.2014–30.6.2014.

The research data was used in the investigation of the efficiency of different criteria for a successful bucking instruction of timber trade. Actually, the stem bucking outcome of the stands was considered as the indicator. The results of the bucking outcome were calculated after the following timber trade simulations (Tables 1 and 2): 1) reference using stem bucking instruction files of production 1.7.2013–30.6.2014, 2) stand classification using instruction files prepared from planning information provided by timber purchase managers (Scenario 1), 3) stand classification using instruction files from real production information measured by harvester (Scenario 2), and 4) implicit stand classification using instruction files prepared from sawmill's production value of logs (Scenario 3). Stem bucking of the timber trade simulations was executed using Ponsse Optisimu software.

Two stand classifications (scenarios 1 and 2) were constructed using the following limits of the average volume of stems in stand removal: 650 dm^3 ("Small stem"), 650–860 dm^3 ("Medium stem") and >860 dm^3 ("Large stem"). The price values of log dimensions for the matrices 5, 6 and 7 were calculated as average values from the price values of the matrices 1, 2, 3 and 4. The efficient criteria were selected by evaluating the goodness of stem bucking outcome for maximizing the monetary value of timber trade with the following attributes;

- Forest owners as the customer on the timber trade: utilization of a log section of the stem (volume, length, top diameter of log section), the log percentage, log's dimensions (volume, length, top diameter of the log) and the monetary value of the stand.
- Sawmill as the customer: the apportionment degree, logs' reject percentage and the relative production value of logs.

The apportionment degree, the production values and the reject percentage were measured at the batch level of harvesting sites (i.e. the combination of 1…n stands). The rest of the attributes were the harvesting site-specific (stand-specific) variables.

III. RESULTS

3.1 Accuracy of forest information for stand classification

Mechanized harvesters cut stands, which produced the share of Small spruce log stems, on average, 21%, while the share of the Medium and Large stems was 41% and 38%, respectively (Figure 4). There was the statistically significant difference between the shares of produced and predicted Small spruce log stems, when the share of produced log stems was compared to the predictions of purchasing managers of the forest industry. The purchasing managers overestimated the volume of Small log stems (Figure 4).

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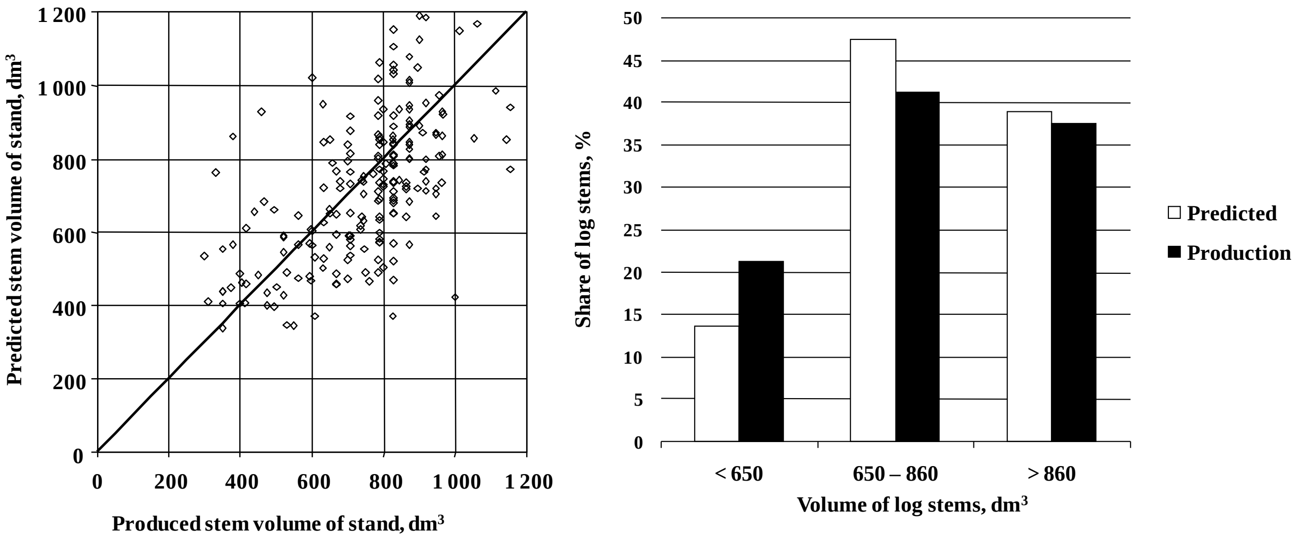

Fig.4: Comparison of produced (harvester) and predicted (purchase managers) stem volumes of Norway spruce stands.

3.2 Simulation of stand classification and monetary value classification

The consequences of stand classification were significant in the stem bucking to logs (Table 3) at the forest level. When the accuracy of the forest information for the stand classification was good (scenario 2), the utilization of a log section of stems was more successful as it is compared to scenario 1: the total volume of logs was larger (0.5%), the number of logs was lower (1.0%) and the average volume of logs was larger (1.5%). When the monetary value approach (scenario 3) was used, i.e., sawmill's production value of logs instead of even prices in the price matrices, the total volume of logs was smaller (1.5%). Furthermore, the number of logs was lower (6%). Consequently, the average volume of logs was larger (5%).

3.3 Criteria for timber trade

The relationships of three criteria were assessed on the selection of successful bucking instruction for the timber trade. When the log percentage is high, the utilization of log section of stems is higher, which can be used as the criterion of forest owners in the timber trade. Figure 5 shows that the log percentage slightly increased, when the stand classifications 1 and 2 (scenarios 1 and 2) were used in the stem bucking simulations. However, the criterion value decreased (1.7%) in the monetary value classification (scenario 3), when sawmill's production value of logs was used in the timber trade simulation.

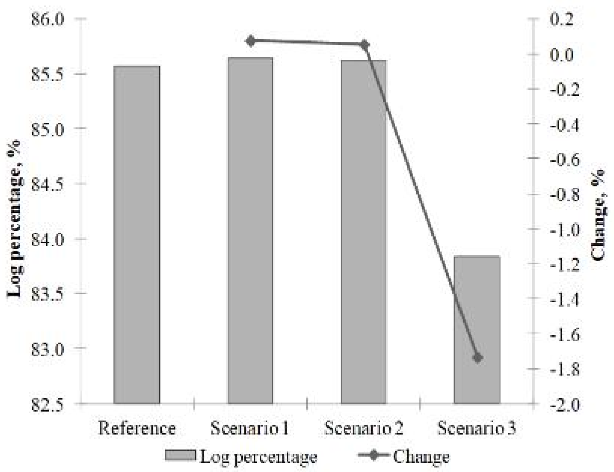

Fig.5: Effects of stand classification (scenarios 1 and 2) and monetary value classification (scenario 3) on log percentage.

In the next assessment, Figure 6 shows that stands' value (€) increased, when the stand classifications 1 and 2 were used in the simulations, which can be used as the criterion of forest owners in the timber trade. In this respect, the best result (0.8%) was achieved, when the stand classification was used with accurate forest information.

Table.3: The effects of the stand classification (scenarios 1 and 2) and monetary value classification (scenarios 3) on the stem bucking in Norway spruce stands.

	Reference	Scenarios		
		1	2	3
Volume of logs [m³]	65,500	65,600	65,800	64,400
Number of logs	287,000	283,500	284,500	269,000
Log's volume [dm³]	228	231	232	240

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Finally, the relationship of logs' production value to stand classifications and monetary value classification was assessed after the timber trade simulation (Figure 7). The relative production value of logs (€/m^3) was lower (1.6%) with the reference, when it was compared to the simulation with the monetary value classification (scenario 3). Correspondingly, the relative production value of logs was lower (1.3%), when the stand classifications (scenarios 1 and 2) were used in the simulation.

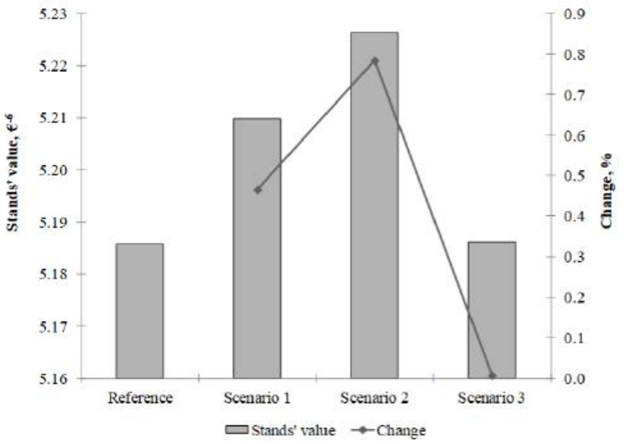

Fig.6: Effects of stand classifications (scenarios 1 and 2) and monetary value classification (scenario 3) on stands' value (€).

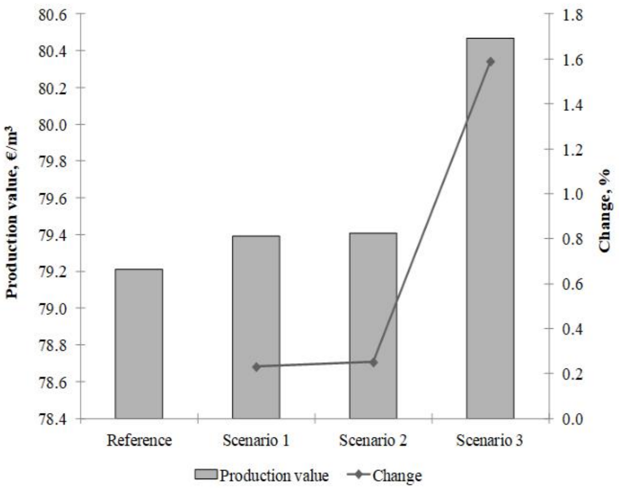

Fig.7: Effects of stand classification (scenarios 1 and 2) and monetary value classification (scenario 3) on relative production value of logs (€/m3).

There was an interesting connection between two criteria, the relative production value of logs and the stands' value, because the monetary value changes were positive in the scenario 2. On the other hand, the stands' value was significantly lower, when the monetary value classification (scenario 3) was used in the timber trade. These criteria can be used for considerations of preferences of forest owners and forest industry in the multi-objective timber trade.

IV. DISCUSSION AND CONCLUSIONS

The objective of this research is to investigate softwood log buying from forest owners and also to evaluate potential effects of lumber production on the timber trade using scenarios involving multiple criteria for maximizing monetary value of timber trade. A simulation model of timber trade was first used to determine the baseline softwood log supply on Norway spruce (Picea abies L. Karst.) stands (total volume of logs, number of logs and log's size). The baseline results were then compared with the results from the three alternative scenarios of timber trade incorporating the parameter and attribute changes in local wood procurement conditions. The bucking outcome of simulations revealed the effects of utilization of multiple criteria on timber trade. Log bucking with baseline instructions would provide the largest number of softwood logs for sawmill; however, there would be a significant change in the total volume of logs and log's size of log delivery to sawmill in the alternative timber-trade scenarios. The bucking instruction of monetary value classification (scenario 3) would decline number of softwood logs based on the effects on sawmill's production value of logs. This result is consistent with Bergstrand 1994, Möller and von Essen 1997, Malinen and Palander 2004 and Kivinen 2006, who found that the bucking-to-demand system can increase the monetary value in the added value chain, despite the timber supply constraints imposed by changed log distribution of stand for achieving a more customized wood procurement.

The simulation results also show that the share of log section removal of stands (m^3) decreased in the bucking outcome, when the production value of logs was used in the price matrix. There was the significant difference in the log percentage (1.7%) criterion at the forest level between the monetary value classification (scenario 3) and the reference (baseline). On the other hand, the results of multi-criteria timber trade analysis suggested that the largest beneficiaries of the stand classification would be forest owners (in criteria of log percentage and stand value) due the stand classification with accurate forest information (scenario 2) increasing by 1.7% (from 83.8% to 85.7%) and by 0.8% (from 5.188 to 5.228 million €), respectively. In addition, the increase in the stands' value also support the findings of Nakahata et al. (2014), who used accurate stand data to examine the optimal bucking to maximize profits in commercial harvesting operations. They observed that considering log sizes could help determine the optimal harvesting of different stands, due to significant differences with respect to stems with a diameter (1.3 m) less than 20 cm. According to several studies, it is also useful to conduct optimal bucking with a consideration of harvesting costs and profitability as well as revenue (Akay et al. 2010, Haynes and Visser 2004,

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Olsen et al. 1991, Sessions et al. 1989, Wang et al. 2009), although a construction of a comprehensive system for wood procurement is impossible (Palander 1998).

Depending on the aspects with which the timber-trade criterion evaluates the goodness of stem bucking outcome for forest owners or sawmill customers, two recommendations for the utilization of timber-trade criteria can be drawn up for maximization of timber trade value:

- If the ultimate goal for stem bucking is to maximize logs' monetary value for sawmill customer in logs' cutting, i.e. production value of logs, then the results suggest that stems' relative monetary value (€/m^3) must be maximized.
- If the main stem bucking goal is other than the maximum monetary value of logs for sawmill customer, then the results suggest that you must maximize the log percentage (%) and stand's monetary value (€).

The log payments to forest owner or the log valuations to sawmill can traditionally be based on the price matrix in the bucking-to-value system. Actually, we used even-value price lists in the bucking-to-demand system in the reference, scenario 1 and scenario 2. The price list was changed in the scenario 3. In theory, when changing to a bucking-to-demand system, sawmill customer should compensate for the potential monetary value discrepancy (stand value loss for the log seller). However, determination of this discrepancy is problematic in timber trade markets. Therefore, a compromise solution between two recommendations (A and B above) with the utilization of stand classification suggested in this study would be beneficial to both forest owner and sawmill customers. Furthermore, the approach can be based on the accurate stand information.

In theory, the monetary value of timber trade could be maximized by harvester operators' self-bucking. However, it is not a potential approach with spruce log stems in the future (Kärhä 2016). Whatever the timber-trade criteria are in this study, it can be suggested that the harvester operators' self-bucking of stems have to be at the lower level than currently. These results are consistent with Wang et al. (2004, 2009), Akay et al. (2010, 2015), Serin et al. (2010) and Kärhä et al. (2017). On the other hand, harvester operators' self-bucking can be seen as a productivity-decreasing and cost-increasing factor of timber harvesting, because human resources are used for monitoring the quality of harvesting instead of cutting. Furthermore, operators' self-bucking work can also be a causing factor of the psychological stress, because the operator works under the hectic pace and suffer from psychological burden of work (Ovaskainen and Heikkilä, 2007). These results suggest that "socially" cost-efficient wood procurement requires harvester's computer-aided bucking and a semi-automatic planning system for preparing more efficient bucking instructions, which can be supported by a smart stem classification suggested in this study.

Actually, the monetary value of the timber trade and the efficiency of stem bucking could be already increased at the stand level, if the bucking instructions are determined using local forest information. The accuracy of forest information could be increased currently by collecting large forest data files, which would contain stand information from separate geographical areas. Harvesters already record automatically stem data from forests, which could be used for stand classification (Palander et al. 2013). All kinds of pre-measurement systems (Manual, Laser, Machine vision) of timber trade are too expensive and inaccurate when compared to the harvester's measurement system (Murphy 2008). Above mentioned sophisticated digital systems are tested in practice, but the monitoring and maintenance of them are currently too expensive. Two decades ago stands' manual pre-measurement system was used in Finland, but it was omitted for the same reasons. Since, timber purchasing managers have made stands' quality estimation for wood procurement of forest industry. The data collection of this study demonstrated the file systems for geographical data system suggested above. Especially, the stem data of harvester was large. Although, the data of sawmill was smaller, it provided us with reliable results on the lumber production. In the study, the stem size predictions of purchasing managers were utilized as the attributes of the local forest information for the stand classification, because current enterprise resource planning data provides this forest information. The results demonstrated that there is a large difference between harvesters' production figures and related predictions of purchasing managers with volumes of small and medium spruce log stems by stand (cf. Figure 6). This is not a desirable situation when you are maximizing the monetary value of the timber trade. Several developments could be made to current timber harvesting systems to improve the accuracy of the stand information (Palander et al. 2013). At least it will require advanced information systems for stem size data collection by forest harvesters in the future.

The Finnish timber trade market is subject to agreements regarding stem bucking regulations. These agreements could be made on the basis of multiple criteria suggested in this study (the log percentage, value of stand and relative production value of logs) accounting for the effects of stand classification on the timber sales of forest owners and the lumber sales of export companies. Further, the timber trade problem could even be solved by applying multi-objective methods in cutting simulations of wood procurement planning. By using e.g. goal programming, in theory, the criteria of forest owners and sawmill customers are possible to consider at the same time, and to find a compromise solution for the stem bucking instructions of stand by determining target values of criteria to stakeholders in wood procurement planning (Palander 1998). In addition to developing multi-criteria methods for better applicability, development of user interfaces would be a necessity for stakeholders of timber trade. Lessons have been learned during this study as outlined above, and the methods and systems will be developed in future.

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REFERENCES

[1] Akay, A.E., Session, J., Serin, H., Pak, M. and Yenilmez, N. 2010 Applying optimum bucking method in producing Taurus fir (*Abies cilicica*) logs in Mediterranean region of Turkey. *Baltic Forestry*. **16**, 273–279.

[2] Akay, A.E., Serin, H. and Pak, M. 2015 How stem defects affect the capability of optimum bucking method? *Journal of the Faculty of Forestry Istanbul University*. **65**, 38–45.

[3] Bergstrand, K.G. 1990. Fördelningsaptering- ett sätt att tilgodose sågverksönskemål. *Resultat*

[4] *No. 11.* Forskningsstiftelsen Skogsarbeten, Stockholm, Sverige. In Swedish

[5] Bergstrand, K.G. 1994. Fördelningsaptering. In optimal förlust och fördelningsgrad. Dokument. Skogforsk, Stockholm, Sverige. In Swedish

[6] Haynes, H.J.G. and Visser, R.J.M. 2004 An applied hardwood value recovery study in the Appalachian Region of Virginia and West Virginia. *International Journal of Forest engineering*. **15**, 25–31.

[7] Kärhä, K., Änäkkälä, J., Hakonen, O., Palander, T., Sorsa, J-A., Räsänen, T. and Moilanen, T. 2016 Utilization of manual bucking in cutting softwood log stems in Finland. In *From Theory to Practice: Challenges for Forest Engineering. Proceedings and Abstracts of the 49th Symposium on Forest Mechanization*. Gendek, A. and Moskalik, T. (eds). Formec, Warsaw, Poland, pp. 61–67.

[8] Kärhä, K., Änäkkälä, J., Hakonen, O., Palander, T., Sorsa, J-A., Räsänen, T. and Moilanen, T. 2017 Analyzing the Antecedents and Consequences of Manual Log Bucking in Mechanized Wood Harvesting. *Mechanics, Materials Science & Engineering*. 12, 1-15.

[9] Kivinen, V.-P., Uusitalo, J. and Nummi, T. 2005 Comparison of four measures designed for assessing the fit between the demand and output distributions of logs. *Canadian Journal of Forest Research*. **35**, 693–702.

[10] Laukkanen, S., Palander, T. and Kangas, J. 2004 Applying voting theory in participatory decision support for sustainable timber harvesting. *Canadian Journal of Forest Research*. **34**, 1511–1524.

[11] Malinen, J. and Palander, T. 2004 Metrics for distribution similarity applied to the bucking to demand procedure. *International Journal of Forest Engineering*. **15**, 33–40.

[12] Möller, J.J. and von Essen, I. 1997 Fördelningsaptering- en fungerande metod även på små trakter och vid liten tillåten värdeavvikelse. *Resultat No. 14.* Skogforsk, Stockholm, Sverige. In Swedish

[13] Murphy, G. 2008 Determining Stand Value and Log Product Yields Using Terrestrial Lidar and Optimal Bucking: A Case Study. *Journal of Forestry*. **106**, 317–324.

[14] Nagahata, C., Aruga, K. and Saito, M. 2015 Examining the Optimal Bucking Method to Maximize Profits in Commercial Operations. *Croatian Journal of Forest Engineering*. **34**, 45–61.

[15] Näsberg, M. 1985 *Mathematical programming models for optimal log bucking*. D.Sc. (Agr. and For.) thesis. Department of Mathematics, Linköping University, Linköping, Sverige. 199 pp.

[16] Natural Resources Institute of Finland. 2017 *Forest wood removals by forestry centre, statistics*. (accessed on 10 November, 2017).

[17] Olsen, E., Pilkerton, S. Garland, J. and Sessions J. 1991 Computer-aided bucking on a mechanized harvester. *Journal of Forest Engineering*. **2**, 25–32.

[18] Ovaskainen, H. and Heikkilä, M. 2007 Visuospatial cognitive abilities in cut-to-length single-grip timber harvester work. *International Journal of Industrial Ergonomics*. **37**, 771–780.

[19] Palander, T. 1998 *Tactical models of wood-procurement teams for geographically decentralized group decision-making*. University of Eastern Finland, Faculty of Science and Forestry. Joensuu, Finland. 152 pp.

[20] Palander, T., Ovaskainen, H. Tikkanen, L. 2009 Profiles of private forest owners and the importance of landscape-scale management in the timber trade process of Finnish wood procurement. *Forestry*. **82**, 227–239.

[21] Palander, T., Nuutinen, Y., Kariniemi, A. and Väätäinen, K. 2013 Automatic time study method for recording work phase times of timber harvesting. *Forest Science*. **59**, 472–483.

[22] Serin, H., Akay, A.E. and Pak, M. 2010 Estimating the effects of optimum bucking on the economic

value of Brutian pine (*Pinus brutia*) logs extracted in Mediterranean region of Turkey. *African Journal of Agricultural Research*. **5**, 916–921.

[23] Sessions, J., Olsen, E. and Garland, J. 1989 Tree bucking for optimal stand value with log allocation constraints. *Forest Science*. **35**, 271–276.

[24] Wang, J., LeDoux, C.B. and McNeel, J. 2004 Optimal tree-stem bucking of northeastern species of China. *Forest Products Journal*. **52**, 45–52.

[25] Wang, J., Liu, J. and LeDoux, C.B. 2009 A three-dimensional bucking system for optimal bucking of central Appalachian hardwoods. *International Journal of Forest Engineering*. **20**, 26–35.