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A Wood Recovery Assessment Method Comparison between Batch and Cellular Production Systems in the Furniture Industry

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Reference

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ABSTRACT

Enhanced wood recovery mirrors a successful wood manufacturing operation. Studies of wood recovery in secondary wood processing, however, are scarce, particularly in furniture manufacturing. Although recovery rates are under the continuous surveillance of sophisticated technology, this attempt to monitor wood recovery would be especially challenging for small- to medium-sized furniture enterprises, as the capital investment in such technology would be substantial. This would hinder the possibility for improvements in production efficiency of the furniture industry. A methodology of wood recovery assessment in the furniture industry has been developed and proposed but has not been validated with a cellular production system, a different layout process and distinctive machinery, species, and other customer requirements. The objective of this study is to assess the wood recovery protocol individually used in batch and cellular production systems, followed by examining the wood recovery of furniture manufacturing in these distinct production systems. Two Indonesian medium-sized furniture companies that individually operate batch and cellular production systems were employed, and two methods, mass and volume, were used to assess wood recovery at each furniture-making station. There was a significant difference in cumulative wood recovery rates between batch and cellular production systems. Based on species and product dimensions, the average individual and cumulative wood recovery rates of furniture manufacturing resulted in a significant difference at the resawing and edging station. Large-dimension product recorded higher wood recovery level than small-dimension product. The wood recovery rates at the resawing and edging, surface planing, thickness planing, and trimming stations were mostly influenced by species, the quality of sawn timber, and cutting bills. Meanwhile, wood recovery

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at other stations was affected by product dimension and design. The mass method was the most acceptable method according to the measurement systems analysis.

Keywords

furniture manufacturing, wood recovery assessment method, furniture production systems, Indonesia

Introduction

Wood recovery is one of the most critical applicable efficiency metrics for measuring the number of wood products generated from the amount of timber utilized in wood manufacturing industries.¹ Wood recovery is commonly interpreted as an input and output ratio of lumber. Improved wood recovery reflects a successful wood manufacturing operation as the improvement enhances margin through diminishing production costs by minimizing raw material expenditure and increasing production capacity.^{2,3}

Furniture production, which consists of multiple wood machining stations, should be assessed on its recovery. Indeed, it is an essential evaluation for furniture manufacturers generating high value-added furniture products.⁴ The assessment can help monitor efficiency and productivity to increase profit. However, studies of wood recovery in secondary wood processing are scarce, particularly in furniture manufacturing, compared with primary wood processing, such as sawmilling^{5–7} and veneer production.^{8–10} Although recovery rates are under continuous surveillance and improvement using sophisticated technology (i.e., sensors, X-ray scanning systems), this attempt to improve systems would be especially challenging for small- to medium-sized furniture enterprises, as the capital investment in such technology would be substantial. This most certainly limits the possibility of improvements in production efficiency of the furniture manufacturing industry. Ultimately, a simple and effective method to assess wood recovery that considers the pace and efficiency of wood recovery measurement and data collection, especially during active production processes, is immediately desired by small- to medium-sized furniture producers.

A methodology of wood recovery assessment has been proposed by Prasetyo, Belleville, and Ozarska.¹¹ The methodology was developed in a medium-sized furniture manufacturing company that operates a batch production system, in which a worker had a duty and remuneration to manufacture a certain volume of furniture products within a specific time frame. However, the methodology has not been incorporated with a cellular production system. A cellular production system involves a series of flowing machining processes in which the product or component is processed from a machining station to the following stations throughout the entire series of required machining stations. A different layout process and distinctive machinery influence production and technology capabilities.¹² The wood recovery assessment protocol for the cellular furniture production system needs to be validated to fine-tune detailed stages within the protocol. Moreover, a technical validation of the methodology is required on its use in other furniture companies that have different machinery, species, other customer requirements affecting product specification, and the cutting bill. These factors have an influence on wood recovery. A measurement systems analysis (MSA) validates recovery metrics and wood recovery measurement methods to control the quality of data collection.¹³ Ultimately, the comparison of wood recovery assessment methods in batch and cellular furniture production systems contributes to the immediate interests of furniture manufacturers. This validation is an important element in ensuring that the wood recovery assessment methodology is reliable and widely implemented in the furniture manufacturing industry worldwide.

The present study was part of a research project aimed at improving the production efficiency of the furniture manufacturing process by developing a simple and efficient wood recovery assessment protocol. Therefore, the aims of this study were: (1) to assess the wood recovery protocol used in two companies that operate a batch production system and a cellular production system, respectively; (2) to examine and compare the wood recovery of furniture production in these distinct production systems; and (3) to adjust the proposed methodology based on the additional parameters of production methods.

Materials and Methods

SELECTION OF THE WOOD FURNITURE MANUFACTURING COMPANIES

Two representative medium-sized wood furniture manufacturing companies in the Jepara region of Central Java Province, Indonesia, were randomly selected for the study and are subsequently referred to as the “batch company” (operating a batch production system) and the “cellular company” (operating a cellular production system) (Table 1). The selection criteria were medium-sized companies employing between 20–99 workers,¹⁴ an in-house furniture production, the use of plantation-grown timber, and a willingness to be part of the research project and implement recommendations from the study.

The batch furniture company operates a batch furniture production system where each worker produces a certain volume of a specific furniture product. The worker operates a machining station individually throughout all required machining stations (from the resawing and edging station to the assembling stations). The cellular furniture company operates a production system in which each worker operates a machine to manufacture a certain component or product with a specific task. The component or product is thus processed from one machining station to the next throughout the series of machining stations required.

WOOD RECOVERY ASSESSMENT

Production Current Furniture Processes

In the batch company, two types of headboard products made from mango (*Mangifera indica*) and mahogany (*Swietenia mahogany*) timbers with distinctive designs were examined (Table 2). The headboard production represented the entire furniture production process as all furniture-making stations were involved. Each machining station in the headboard manufacturing process was assessed. A detailed batch production layout of headboard products and specimen flows was created. The wood recovery assessment of a batch production system based on a type of product manufactured by a specific skilled worker was conducted by following the movement of the worker and the specimen.

In the cellular company, a total of four products was investigated: two types of chair, a bed frame, and a sofa frame (Table 2). The manufacturing processes of these products represented the entire furniture manufacturing process as all furniture manufacturing stations were used. Each machining station in the furniture manufacturing process was assessed for wood recovery. As the cellular company implemented a cellular production system, wood recovery measurement was conducted by following the movement of specimens processed from one machining station to the next throughout the series of required machining stations, whereas the worker’s movement was ignored. A detailed batch production layout of the products and specimen flows was created.

The furniture production in the batch company began at the resawing and edging station, which was comprised of a small headband saw and a circular saw (fig. 1). At this station, a dry rough-sawn timber was converted into pieces of furniture specimens according to a cutting bill. Edging and parallel to the grain-cutting operations were

TABLE 1

Medium-sized furniture company profiles

Profile	Batch Company	Cellular Company
Production capacity, per month:		
- Number of containers	5	2
- Volume, m ³	270	70
Type of furniture product	Indoor	Indoor and customization ^a
Wood species utilized	Mango (<i>Mangifera indica</i>) Mahogany (<i>Swietenia mahogany</i>) Teak (<i>Tectona grandis</i>)	Teak (<i>Tectona grandis</i>) White oak (<i>Quercus alba</i>)
Number of employees	83	63
Export destinations	United States, Denmark, and France	Taiwan, Hong Kong, Singapore, Middle East, and France

Note: ^a Customization: indoor products with specific dimensions based on customer requirements.

TABLE 2

Specifications of furniture products examined at the batch and cellular companies

Company	Type of Product	Dimension, D/T × W × L, cm	Species	Type of Finishing
Batch	Headboard 1	7 × 205 × 138	Mango	Colored polyurethane
	Headboard 2	7 × 205 × 138	Mahogany	Colored polyurethane
Cellular	Chair 1	44 × 45 × 84	Teak	Polyurethane
	Bed frame	170 × 210 × 110	Teak	Polyurethane
	Sofa frame	185 × 74 × 60	Teak	Polyurethane
	Chair 2	57 × 53 × 79.5	White oak	Oil

Note: D: depth; T: thickness; W: width; L: length.

accomplished using the small band saw, whereas cross-cutting was accomplished using the circular saw. The following station was the surface planing station 1, at which the two sides of the specimens were machined to be evenly flat and truly square. This operation anticipated an overplaning action that was due to the drying defects of timber, such as bowing, cupping, diamonding, etc. The two flat and square sides of the specimen were used as guiding sides to plane the thickness in the thickness planing station. The square specimens were then planed in the thickness planing station to create a consistent and similar thickness. After gaining a consistently desired thickness, the specimens were planed back into the surface planing station 2 to ensure that other unplanned sides of the specimens were flat and square. This operation was also the final checkpoint for squareness before being glued and jointed. The mortising/jointer, gluing, and jointing processes were then incorporated in the assembly process in a closed area. In these processes, large-dimension specimens were made using end- or side-gluing techniques, and then the specimens were planed using a master planer. To attain the desirable dimension of specimens, the end-trimming station was employed before sending these specimens to the assembly station. After the furniture components had been assembled, the furniture parts that required carving were then carved using handy carving tools and a manual carving operation. The sanding station was the final station before they were sent to the finishing department.

The first four furniture-making stations and the functions of these stations in the cellular company were basically similar to the batch company, but there was only one surface planing station in the cellular company (fig. 2). The surface planing process flattened four sides evenly and square at the same time. After the specimens had been trimmed at the end-trimming station, the specimens were processed at the tenon, mortise, or spindle-molding station, depending on the design of the products. A tenon produces a tongue, whereas a mortise creates a cavity. These stations were employed to make a mortise and tenon joint connecting two furniture specimens. A spindle molder was used to create decorative edges, long connectors, and bend shapes. All specimens were then processed in the gluing and jointing station to generate large-dimension specimens and assemble the

FIG. 1

Production layout of batch company: 1, edging; 2, resawing; 3, surface planing 1; 4, thickness planing; 5, surface planing 2; 6, mortising and jointer; 7, gluing and jointing; 8, master thickness planing; 9, end trimming; 10, carving and assembling; 11, sanding.

FIG. 2

Production layout of cellular company: 1, edging; 2, resawing; 3, surface planing; 4, thickness planing; 7, gluing and jointing; 9, end trimming; 10, carving and assembling; 11, sanding; 12, spindle molding; 13, tenon; 14, mortise.

furniture components. Products from furniture specimens using connectors, joints, and gluing techniques were constructed at the assembling station. Finally, rough furniture products were sanded before being sent to the finishing station.

Data Collection

The quality and dimensions of the sawn boards utilized for the wood recovery study were assessed using Indonesian National Standards SNI 7539.1.2010, *The Sawn Timber of Teak: Classification, Requirement, and Marking*,¹⁵ and SNI 7537.2.2010, *Sawn Timber: The Dimension Measurement*.¹⁶ The moisture content was determined based on the Australian and New Zealand standard AS/NZS 4787, *Timber-Assessment of Drying Quality*,¹⁷ and use of a resistance moisture meter.

At a minimum, 30 specimens were measured per station. Each individual component was marked and tracked along the manufacturing process. Batch measurements in the batch and cellular production systems involved measuring a number of specimens machined together at each processing station. The specimens were then conveyed to the next station. Input and output were measured for each processing station, except for the gluing and jointing station.

Two measures were used for the input and output at each station: volume and mass measures (Table 3). For volume, three dimensions were measured on every specimen: (1) length, cm, (2) width, cm, and (3) thickness, mm. Length was measured at one position, in the middle of the widest section of a specimen. Width and thickness were measured at three positions, one measure at each end and another in the middle. Mass measurement was conducted using a standard balance (± 0.1 kg) with specimens being weighed before and after each processing station. When output measurements were undertaken to quantify processed specimens, usable offcuts were also collected and included if they were then further utilized. Standard deviation of wood recovery rates and an MSA

TABLE 3

The procedure for quantifying output from input

Input	Station	Output Scenario	Measurement
A sawn board or a specimen	Edging and resawing (1 & 2), and end trimming (9)	2 specimens	L, W
		2 specimens and 1 offcut	
		1 specimen and 1 offcut	
	Surface planing (3 & 5), thickness planing (4), master thickness planing (8)	1 specimen	W and T
	Tenon and mortise (13 & 14), molding (12), gluing and jointing (7), carving and assembling (10), and sanding (11)	Irregular shape specimens	Weighing specimens

Note: L: length; W: width; T: thickness.

involving specimens, workers, and measurement repeatability were used to maintain quality control of data collection.

The formula for calculating the recovery rate of a specimen using volume and mass methods at every processing station is defined as follows (adapted from USDA¹⁸):

$$Rv_{1,2,3,\dots,n} = \frac{\text{Volume output } S_{1,2,3,\dots,n}}{\text{Volume input } S_{1,2,3,\dots,n}} \times 100 \quad (1)$$

$$Rw_{1,2,3,\dots,n} = \frac{\text{Mass output } S_{1,2,3,\dots,n}}{\text{Mass input } S_{1,2,3,\dots,n}} \times 100 \quad (2)$$

where:

Rv = recovery rate using volume method (%),

Rw = recovery rate using mass method (%), and

$S_{1,2,3,\dots,n}$ = specimen 1,2,3, etc.

The calculations of average recovery rate of n specimens using volume and mass methods at one processing station are, respectively, as follows:

$$R_{Av\ V} = \frac{\sum_{i=1}^n R_V}{n} \quad (3)$$

$$R_{Av\ W} = \frac{\sum_{i=1}^n R_W}{n} \quad (4)$$

where:

$R_{Av\ V}$ = average recovery using volume method (%),

$R_{Av\ W}$ = average recovery using mass method (%), and

n = the number of specimens.

The calculation of the overall rate of all processes using volume and mass methods with an assumption that the furniture manufacturing stations are crosscutting (c), edging (e), planning (p), shaping (h), and sanding (a), is as follows:¹⁸

$$R = R_c \times R_e \times R_p \times R_h \times R_a \quad (5)$$

where R is the cumulative recovery rate at furniture manufacturing process (%).

All data collected were analyzed using Sigma XL Version 8 software (SigmaXL, Kitchener, Ontario, Canada) for graphical and statistical analysis and using a Measurement Systems Analysis (MSA) method. An Anderson-Darling test, test of equal variance, and a two-sample t -test were performed to test the difference between the wood recovery rates measured by the volume and mass methods. This statistical procedure was also applied to analyze the standard deviations for each method to the cumulative and individual wood recovery rate results per product and the average individual and cumulative wood recovery rates for the first four stations. When the data were normal, regardless of whether the variance was equal or nonequal, a two-sample t -test was applied. For the nonnormal data and when the variance was equal, a two-sample Mann-Whitney test was applied. When the variance was not equal for the nonnormal data, the Kruskal-Wallis test was performed. The normal and non-normal data were analyzed using histograms and descriptive statistics.

Results and Discussion

THE CASE STUDY OF THE BATCH COMPANY

As the batch company utilized mango and mahogany timbers harvested from farm and agroforestry, there was no Indonesian standard of sawn timber for these species. Indeed, the local saw millers that converted these timbers into sawn boards were not aware of the application of any standard to their sawn boards.

Table 4 depicts the wood recovery rate assessment of the two types of furniture products produced by the batch company at every station using the mass and volume methods. Every method has two calculations: individual and cumulative calculations. The individual calculation is the calculation of the average recovery rate of n specimens per station, whereas the cumulative calculation is the multiplication of wood recovery rates from all stations involved in the process. The resawing and edging station used two types of saw: a small band saw and a circular saw, respectively. The use of the two saws depended on the defect and size of sawn timber to maximize wood recovery. The station had the lowest wood recovery rates of all of the stations, no matter which products and species were processed. When looking at the individual products and species, the wood recovery rate of the headboard 1 (mango) at the resawing and edging station ranged from 67.3 ± 16.7 % to 77.1 ± 17.0 %, which is the lowest rate among all stations. This low wood recovery rate was then followed by the rates generated by the first thickness planing, end trimming, and the second surface planing stations; these results are similar to those of a study conducted by Prasetyo, Belleville, and Ozarska.¹¹ For the headboard 1 product, the second surface planing station was required in order to machine the specimens square because the characteristics of sawn mango boards tend to have wane or be unsquared (diamond defect). This station generated a low recovery (86.4 ± 2.6 %), followed by mortising or routing, carving, and first surface planing stations, which were 90.0 ± 1.6 %, 91.0 ± 3.4 %, and 92.5 ± 6.4 %, respectively. The sanding and the second thickness planing required after the jointing and gluing and the assembly stations did not remove a high volume of wood.

For the headboard 2 (mahogany), the lowest wood recovery rate was gained by the second thickness planing station (52.0 ± 12.8 %). The station dressed the surface of the specimens after they were glued and joined together. As the surface of mahogany sawn boards was wavy because of improper drying, the second planing station dressed a high volume of wood. The second highest wood recovery rate occurred at the resawing and edging station (74.0 ± 14.7 – 14.8 %), followed by the end trimming and first surface planing stations, which were 74.3 ± 8.7 % and 81.3 ± 10.8 % to 88.3 ± 9.8 %, respectively. The thickness planing, mortising, carving, assembly, sanding, and jointing and gluing stations generated high recovery rates.

The average cumulative wood recovery rate for the 11 stations in the batch company was 23.7 %, which was based on the mass method (**Table 5**). The result was much lower compared with the results of a study conducted by Prasetyo, Belleville, and Ozarska.¹¹ In that study, three qualities of teak utilized in a batch furniture-making company resulted in 26.2 % of the average cumulative wood recovery rate. The result from the current study was also lower than the result recorded in a study conducted by Nainggolan et al.¹⁹ in Indonesia, which recorded 38 % of the wood recovery level in the Indonesian furniture manufacturing industry. The resawing and edging, the second thickness-planing, and end-trimming stations recorded lower individual wood recovery rates than the remaining stations, which were 70.7 ± 15.8 % to 75.6 ± 15.9 %, 75.0 ± 7.3 %, and 77.7 ± 8.7 %, respectively. These lower results for the average cumulative wood recovery rates were followed by wood recovery rates at the first and second surface-planing, and the first thickness-planing stations that were 86.9 ± 8.6 % to 89.2 ± 8.0 %, 86.4 ± 2.6 % to 88.9 ± 2.9 %, and 86.6 ± 4.9 % to 87.5 ± 4.1 %, respectively. There was no significant difference ($P > 0.05$) between the volume and mass methods and the standard deviations of each method employed in the assessment of the wood recovery rate in the furniture manufacturing process. This statistical result was similar to the result of the wood recovery assessment methodology proposed and developed by Prasetyo, Belleville, and Ozarska.¹¹

THE CASE STUDY OF THE CELLULAR COMPANY

The quality of the sawn teak timber did not meet the criteria of SNI 7539.1:2010 because the teak logs were converted into rough sawn timber without applying SNI standards. Additionally, no standard was applied to

TABLE 4

Individual and cumulative wood recovery results (%) per product of the batch company

			Station										
			Resawing and Edging	First Surface Planing	First Thickness Planing	Second Surface Planing	Mortizing/ Routing	Jointing and Gluing	Second Thickness Planing	End Trimming	Assembly	Carving	Sanding
Product	Method												
Headboard 1 (mango)	Mass	Individual	77.1 ^a	92.5	80.2	86.4	90.0	100	98.0	81.0	100	91.0	98.0
			17.0 ^b	6.4	3.7	2.6	1.6	0	1.7	8.7	0	3.4	2.8
			30 ^c	30	30	30	30	30	30	30	30	30	30
		Cumulative	77.0	71.2	57.1	49.3	44.4	44.4	43.5	35.2	35.2	32.1	31.4
	Volume	Individual	67.3	90.0	83.0	92.0							
			16.7	6.2	3.9	2.9							
			30	30	30	30							
		Cumulative	67.3	60.6	50.3	46.3							
	Headboard 2 (mahogany)	Mass	Individual	74.0	81.3	94.8		93.0	100	52.0	74.3	99.0	93.0
14.7				10.8	4.5		4.6	0	12.8	8.7	0.3	1.5	1.4
30				30	30		30	30	30	30	30	30	30
		Cumulative	74.0	60.2	57.0		53.0	53.0	27.6	20.5	20.3	18.9	18.5
Volume		Individual	74.0	88.3	90.1								
			14.8	9.8	5.8								
			30	30	30								
		Cumulative	74.0	65.3	58.9								

Note: ^a average; ^b standard deviation; ^c number of specimens.

TABLE 5

Average individual wood recovery rates (%) and cumulative wood recovery rates for the headboard products (%) per station of the batch company

Method		Station										
		Resawing and Edging	First Surface Planing	First Thickness Planing	Second Surface Planing	Mortizing/Routing	Jointing and Gluing	Second Thickness Planing	End Trimming	Assembly	Carving	Sanding
Mass	Individual	75.6 ^a	86.9	87.5	86.4	91.5	100	75.0	77.7	99.5	92.0	98.0
		15.9 ^b	8.6	4.1	2.6	3.1	0	7.3	8.7	0.2	2.5	2.1
		60 ^c	60	60	60	60	60	60	60	60	60	60
	Cumulative	75.6	65.7	57.4	49.6	45.4	45.4	34.1	26.4	26.3	24.2	23.7
	Volume	70.7	89.2	86.6	88.9							
		15.8	8.0	4.9	2.9							
		60.0	60.0	60.0	60.0							
	Cumulative	70.7	63.0	54.5	48.5							

Note: ^a average; ^b standard deviation; ^c number of specimens.

TABLE 6

Individual and cumulative wood recovery results (%) per product of the cellular company

Product	Method		Station							
			Resawing and Edging	Surface Planing	Thickness Planing	End Trimming	Spindle Molding	Tenon	Mortising	Sanding
Chair 1	Mass	Individual	52.9 ^a	94.6	83.3	93.8	84.5	90.6	91.2	95.3
			9.6 ^b	4.3	2.8	3.2	4.5	4.8	2.6	1.8
			30 ^c	30	30	30	30	30	30	30
	Volume	Cumulative	52.9	50.1	41.7	39.1	33.1	29.9	27.3	26.0
		Individual	64.5	93.0	82.8	94.9				
			9.9	4.1	2.7	3.3				
			30	30	30	30				
		Cumulative	64.5	60.0	49.7	47.2				
Bed frame	Mass	Individual			83.0	92.8		90.9	99.1	97.5
					4.6	4.2		2.7	0.1	1.6
					30	30		30	30	30
	Volume	Cumulative			83.0	77.0		70.0	69.3	67.6
		Individual			81.4	92.1				
					4.2	4.3				
					30	30				
		Cumulative			81.4	74.9				
Sofa frame	Mass	Individual	53.6		84.2			96.0	94.1	97.3
			9.8		6.8			1.6	1.8	1.4
			30		30			30	30	30
	Volume	Cumulative	53.6		45.1			43.3	40.8	39.7
		Individual	56.5		82.8					
			10.1		6.6					
			30		30					
		Cumulative	56.5		46.8					
Chair 2	Mass	Individual	69.5	92.2	80.1	87.5	85.4	88.7	93.4	96.1
			8.8	5.3	11.2	3.2	6.1	5.7	1.2	1.4
			30	30	30	30	30	30	30	30
	Volume	Cumulative	69.5	64.1	51.3	44.9	38.4	34.1	31.8	30.6
		Individual	71.3	94.7	81.3					
			9.1	5.1	11.0					
			30	30	30					
		Cumulative	71.3	67.5	54.9					

Note: ^a average; ^b standard deviation; ^c number of specimens.

the white oak used. This case was similar to the wood quality assessment conducted by Prasetyo, Belleville, and Ozarska.¹¹ The sawn teak boards were then assessed according to the grading standard of the cellular company derived from the customer requirements. The grade of teak was classified as quality B (≤ 2.5 -mm knots), a medium proportion of sapwood (≤ 40 %), no decay, small oil canal, and nonuniform color).

The resawing and edging station used small band saws and a circular saw to optimize the initial converting process. The station generated the lowest wood recovery rate of all of the stations, no matter which product was manufactured, and ranged from 52.9 ± 9.6 % to 71.3 ± 9.1 % (Table 6). Looking at the individual products, products made from teak, such as chair 1 and the sofa, had lower recovery rates at the resawing and edging station than did chair 2, which was made from white oak (Table 7). This represented the utilized quality of teak and white oak, where the quality of white oak was higher than the quality of teak.

For the chair products, the resawing and edging station achieved the lowest wood recovery rate for both chair 1 and chair 2, which ranged from 52.9 ± 9.6 % to 64.5 ± 9.9 % and from 69.5 ± 8.8 % to 71.3 ± 9.1 %, respectively.

TABLE 7

Average individual wood recovery rates (%) and cumulative wood recovery rates for all of the products (%) per species per station of the cellular company

Species	Method		Station							
			Resawing and Edging	Surface Planing	Thickness Planing	End Trimming	Spindle Molding	Tenon	Mortising	Sanding
Teak	Mass	Individual	53.3 ^a	94.6	83.5	93.3	84.5	92.5	94.8	96.7
			9.7 ^b	4.3	4.7	3.7	4.5	3.2	2.2	1.6
			90 ^c	90	90	90	90	90	90	90
	Volume	Cumulative	53.3	50.4	42.1	39.3	33.2	30.7	29.1	28.2
		Individual	60.5	93.0	82.3	93.5				
			9.9	4.1	4.5	3.8				
			90	90	90	90				
		Cumulative	60.5	56.3	46.3	43.3				
	Mass	Individual	69.5	92.2	80.1	87.5	85.4	88.7	93.4	96.1
			8.8	5.3	11.	3.2	6.1	5.7	1.2	1.4
			30	30	230	30	30	30	30	30
		Cumulative	69.5	64.1	51.3	44.9	38.4	34.1	31.8	30.6
		Volume	71.3	94.7	81.3					
			9.1	5.1	11.0					
			30	30	30					
		Cumulative	71.3	67.5	54.9					

Note: ^aaverage; ^bstandard deviation; ^cnumber of specimens.

This was followed by the thickness-planing and spindle-molding stations, which achieved a wood recovery rate of 83.3 ± 2.8 % to 82.8 ± 2.7 % and 84.5 ± 4.5 %, respectively, for chair 1, and 80.1 ± 11.2 % to 81.3 ± 11.0 % and 85.4 ± 6.1 %, respectively, for chair 2. High rates of wood recovery were achieved for both chairs at the rest of the stations.

The manufacturing of the specimens of the bed frame product started at the thickness planning station because specimens of the required dimensions were produced in the saw mill. The designs of the bed frame and the sofa frame were simple and, based on the product dimensions, were categorized as a large-dimension product.

The thickness planing station recorded the lowest wood recovery rate (81.4 ± 4.2 % to 83.0 ± 4.6 %) among all stations. The lowest recovery occurred at the resawing and edging station (53.6 ± 9.8 % to 56.5 ± 10.1 %), followed

TABLE 8

Average individual wood recovery rates (%) and individual wood recovery rates for all of the products (%) per station of the cellular company

Method			Station							
			Resawing and Edging	Surface Planing	Thickness Planing	End Trimming	Spindle Molding	Tenon	Mortising	Sanding
Mass	Individual	61.4 ^a	93.4	81.8	90.4		85.0	90.6	94.1	96.4
		9.4 ^b	4.8	6.4	3.5		5.3	4.0	1.9	1.5
		120 ^c	120	120	120		120	120	120	120
	Cumulative	61.4	57.4	46.9	42.4		36.1	32.7	30.7	29.6
	Volume	65.9	93.8	81.8	93.5					
		9.7	4.6	6.1	3.8					
		120	120	120	120					
	Cumulative	65.9	61.8	50.6	47.3					

Note: ^aaverage; ^bstandard deviation; ^cnumber of specimens.

TABLE 9

Summary of wood recovery assessment from the two case studies

Sets	Batch Company	Cellular Company
Production system	Batch	Cellular
Species	Mango and mahogany	Teak and white oak
Product	Headboards	Chairs, bed frame, and sofa frame
Number of station	11	8
Number of samples	60	60
Mean percentage of the cumulative wood recovery rates (based on the mass method)	23.7	29.6
Standard deviation	3.2	2.1
<i>t</i> -Test (the mass method)		−7.29*
Mean time of measuring wood recovery per specimen:		
- Mass method, s	21	18
- Volume method, s	69	63

Note: *Significant at an α of 0.05 according to the Mann-Whitney *t*-test.

by the thickness-planing station (82.8 ± 6.6 % to 84.2 ± 6.8 %). The rest of the stations recorded high recovery rates. Comparing wood recovery of all the products, there was a significant difference in cumulative wood recovery rates ($t = -11.36$). The small-dimension products (chairs 1 and 2) had lower wood recovery levels than the large-dimension products (the bed frame and the sofa frame).

The comparison with two other species, teak and white oak, did not yield a significant difference in the cumulative wood recovery of the two species. However, the quality of white oak was much better than the quality of teak. This was represented by the significantly different wood recovery rates at the resawing and edging station at which white oak achieved 69.5 ± 8.8 % to 71.3 ± 9.1 % of wood recovery, whereas teak recorded 53.3 ± 9.7 % to 60.5 ± 9.9 % of wood recovery. The recovery rates of the end-trimming station for both teak and white oak were similar, which were 93.3 ± 3.7 % and 87.5 ± 3.2 %, respectively. However, the factors affecting the recovery at this station was not only the quality of species but also the design of the products. Furthermore, the varied wood recovery rates at the tenon station were mostly influenced by product design. The rest of the stations had similar wood recovery rates.

The average cumulative wood recovery rate for the eight stations in the cellular company was 29.6 %, which was based on the mass method (Table 8). This was higher than the result of the batch company, which was 23.7 %, and higher than the results obtained in the previous study conducted by Prasetyo, Belleville, and Ozarska,¹¹ which was 26.2 %. The wood recovery rate of the cellular company was lower compared with the research finding by Nainggolan et al.,¹⁹ which was 38 %. The resawing and edging, thickness-planing, and spindle-molding stations recorded lower individual wood recovery rates than the remaining processes, which were 61.4 ± 9.4 %, 81.8 ± 6.4 %, and 85.0 ± 5.3 %, respectively.

TABLE 10

Analysis of the individual and cumulative wood recovery rate according to species and product dimension

Parameter	Statistical Analysis Method	<i>n</i>	Station (Individual Wood Recovery)			Cumulative Wood Recovery	
			Resawing and Edging <i>t</i> / <i>F</i>	Subset Group and Tukey's HSD Test		<i>t</i> / <i>F</i>	Subset Group and Tukey's HSD Test
Species	One-way ANOVA (<i>F</i>)	30	46.21*	mango ^{AB} ; white oak ^A ; teak ^B ; mahogany ^A ; Tukey's HSD = 5.01		42.98*	mango ^A ; white oak ^A ; teak ^A ; mahogany ^B ; Tukey's HSD = 2.24
Product Dimension	<i>t</i> -test (<i>t</i>)	30	−9.56*			−11.36*	

Note: *Significant at an α of 0.05 according to the Mann-Whitney *t*-test (*t*); for a given test, species names followed by the same letter in the subset group did not differ significantly ($\alpha = 0.05$) according to the one-way ANOVA (*F*); *n* = number of specimens.

respectively. These lower results for the average cumulative wood recovery rates were followed by the wood recovery rates at the end-trimming and tenon stations that were $90.4 \pm 3.5\%$ and $90.6 \pm 4.0\%$, respectively.

Using the same methodology to compare the average cumulative and individual wood recovery rates for the first four stations and the overall and individual wood recovery rate results per product in the batch company, no significant differences between the volume and mass methods were found in the cellular company, including the standard deviations of each method used ($P > 0.05$). Similar results were obtained in the study by Prasetyo, Belleville, and Ozarska.¹¹

ANALYSIS OF WOOD RECOVERY ASSESSMENT FROM THE TWO SELECTED COMPANIES

Based on a two-sample Mann-Whitney test, there was a significant difference between the batch company and cellular company (t -test = -7.29) in cumulative wood recovery rates using the mass method (Table 9). The difference was mostly influenced by the production system, whereas at the cellular company, each worker was only responsible for one specific machining process. It can be seen from the percentage contribution of variance component that the standard deviation of wood recovery measurement of all stations at the cellular company using the mass method were 11.2 and 0.24 %, respectively (see fig. 3). The deviation of recovery rates in the batch company was higher than those in the cellular company, which was up to 17.0 % of the contribution of variance component and 0.39 % of the standard deviation (the mass method).

The average time required to perform the mass method (to weigh each specimen, capture the data, and record the data manually) was 21 s at the batch company and 18 s at the cellular company. Using the volume method, 69 and 63 s was required, on average, at the batch and cellular companies, respectively. The process of using the mass method was very fast and efficient. Only one data point per specimen was recorded using the mass method, whereas seven data points were recorded using the volume method. The seven data points were used to control dimensional variations between and within the measured specimens. However, the precision of the data using both methods, i.e., the standard deviation, was not significantly different. These results were in accordance with the wood recovery assessment conducted by Prasetyo, Belleville, and Ozarska.¹¹ This indicates that the types of a production system, species, product, number, and types of station or machinery used do not affect the measurement process of the wood recovery assessment.

A variance analysis was also performed to compare the wood recovery rates of individual products and stations (Table 10). Two parameters were derived from the product specifications: (1) types of species (mango, mahogany, teak, and white oak) and (2) product dimensions, which were derived from the teak products in the cellular company: small (chairs 1 and 2) and large (bed frame and sofa frame). A multivariate chart and two statistical analyses (t -test and analysis of variance (ANOVA)) were applied, which were then followed by the advanced multiple comparison tests using Tukey's honest significant difference (HSD) test with a subset group.

A significant difference in the wood recovery rate only occurred at the resawing and edging station for the individual wood recovery rate per station, at which the product of large dimension recorded a higher wood recovery level than that of small product dimension ($t = -9.56$). Product dimension also significantly affected cumulative wood recovery, revealing that the large-dimension product recorded higher wood recovery levels than did the small-dimension product ($t = -11.36$). These results aligned with the product dimensions of teak products in the study conducted by Prasetyo, Belleville, and Ozarska,¹¹ especially at the initial machining stations. The operations at the stations are also related to the dimensions or design and quality of the utilized timber, listed technically on the cutting bill.^{20,21} Furthermore, the relationship between wood recovery, lumber dimensions, and lumber parts have been thoroughly researched by Thomas,²² Gatchell, Anderson, and Araman,²³ Wiedenbeck and Araman,²⁴ and Hamner, Bond, and Wiedenbeck.²⁵ However, this study places further emphasis on the relationship between wood recovery per station and cumulative recovery (whole furniture manufacturing process) and product dimensions.

According to the species utilized, covering the wood quality of the species, the individual wood recovery rate of furniture manufacturing resulted in a significant difference at the resawing and edging station ($F = 46.21$). This

difference was related to the wood quality, as determined by the customer's product requirements. White oak had the best wood quality among the species. Although mango and mahogany timbers were of lower quality than teak, the wood recovery rates of teak were lower than the recovery rates of the lower-quality species. This was caused by customer requirements that demanded use of a high proportion of heartwood to produce uniform color, high durability, and natural appearance. This result is similar to the findings of the study by Prasetyo, Belleville, and Ozarska,¹¹ where different teak quality classes, determined by the heartwood proportion and the type of finishes, were statistically different in the wood recovery rates at the resawing and edging station. Looking at the cumulative wood recovery, different species also recorded a significant difference in the cumulative wood recovery rates measured in the furniture manufacturing process ($F = 42.98$), where the recovery rates of mahogany were lower than the other species. This result corresponds to the study conducted by Gatchell, Wiedenbeck, and Walker,²⁶ which concluded that wood recovery was partly affected by lumber species, mainly in terms of defects and the grain patterns of the species.

Ultimately, from the discussions of each case study, it can be concluded that wood recovery is influenced by species type, the quality of sawn timber, and product dimensions. These results supplement the study conducted by Wengert and Lamb,²⁷ who found that the cost and wood recovery of secondary wood processing was affected by 10 factors: lumber grade, drying quality, cutting bill, operator's skill and decision making, part quality, production layout, kerf, edging practices, lumber size, and lumber grading rules. The wood recovery rates at the first four stations, i.e., the resawing and edging station, surface-planing, thickness-planing, and end-trimming stations, were mostly influenced by species, the quality of sawn timber, and cutting bills (component/product dimension or design). The wood recovery at each station after the first four stations, e.g., mortizing, molding, carving, and gluing and jointing stations, was influenced by product design.

The case studies revealed consistent results from the methodology of wood recovery assessment proposed by Prasetyo, Belleville, and Ozarska.¹¹ The methodology was applied successfully to each company. The application of the methodology for each company assisted to address the technical and nontechnical issues of wood recovery measurement. Implementing the proper and well-established stages of the wood recovery assessment methodology was able to successfully adapt to the technical planning on the production floor, the investigation of current furniture production, the wood recovery measurement, and the data collection.

Both the mass and volume methods could be used to assess the wood recovery rate at four stations: the resawing and edging, surface-planing, thickness-planing, and end-trimming stations, as both methods were not significantly different. The volume method could not be used for measuring specimens with curved, bent, rounded, irregular shapes, or cavities. These specimens were processed at the routing, mortizing, molding, gluing and jointing, carving, and the final trimming stations. The mass method could be used to measure the wood recovery rate at all furniture manufacturing stations as this method can be applied to a wide variety of specimen shapes.

The use of statistical analysis employed in this article can be applied to other wood recovery measurement in other furniture manufacturing companies. This will help users analyze the wood recovery rates of their production system.

It is important to point out that special attention is required when applying the method of wood recovery assessment in a cellular production system. The assessment method should be clearly explained to the operators of all stations because each operator will be involved in the wood recovery measuring process. In addition, as the cellular production system is faster than the batch system and involves many operators, the researchers and the operators should be aware of the codes for specimens, including tracking the specimens throughout the furniture machining stations. Otherwise, the specimens might be lost during the process of the wood recovery measurement.

Wood recovery assessment and control in the furniture manufacturing process in which approximately 50 % of cumulative production costs comprise raw material costs²¹ is of high importance. Therefore, the development and validation of the simple and efficient method proposed by Prasetyo, Belleville, and Ozarska¹¹ should not be underestimated. The method could also be employed as a manual and rapid monitoring method on the production floor. This could be a paramount system for controlling wood recovery in a furniture manufacturing

FIG. 3 Contribution of the variance component, percent total variation, and standard deviation of the wood recovery rate measurement metrics for (A) the volume method and (B) the mass method used in the batch company; (C) the volume method and the (D) mass method used in cellular company. *significant at an α of 0.05 according to the ANOVA with part and operator interaction.

company where the plant lacks a data acquisition system. The current study contributes to managers, supervisors, and researchers of furniture manufacturing operations worldwide.

MSA OF WOOD RECOVERY ASSESSMENT METHOD

In this study, an MSA was performed to validate the wood recovery assessment method employed in batch and cellular companies. The analyzer involved gage repeatability and reproducibility (R&R) analysis (crossed) for validating the proposed methods for the wood recovery rate assessment. The investigated parameters of the MSA in each company were: (1) the specimen (i.e., five sawn boards); (2) operator (three workers); and (3) repeatability (five repetitions for each operator to measure similar specimens). The measurement was conducted by blind and random testing at the resawing and edging station. The analysis of variance with part and operator interaction metrics was also performed using balanced design type.

For the volume method (fig. 3), the wood recovery rate measurement system and the interaction between the system and operator were significant ($P < 0.05$) in the batch and cellular companies. This means that when employing the volume method to assess the wood recovery rate in the furniture-making process, the interaction between the system and operator needs to be considered. Meanwhile, the significant metric of the wood recovery rate measurement system for the mass method in both companies was only the wood recovery measurement system ($P < 0.05$).

According to the Automotive Industry Action Group¹² on gage standards, the contribution of the variance component of the part metric using the volume method in batch and cellular companies was 9.5 and 8.9 %, respectively.

respectively. Based on these results, the method was then categorized as a marginal system (4–10 %). Meanwhile, the contribution of the variance component of the part metric using the mass method in batch and cellular companies was 3.5 and 2.5 %, respectively. The method was then categorized as an acceptable system (<4 %). Both the volume and mass methods had low standard deviations (<2.5).

The gage system of the wood recovery rate measurement method using both the mass and volume methods in batch and cellular companies was reliable, reproducible, and repeatable. For both methods, the contribution of the variance component, cumulative variation, and standard deviation of the part variation were larger than the contribution of the variance component, total variation, and standard deviation of the gage variation. Similar results were obtained when applying the mass method. The results of the MSA of the wood recovery assessment protocol in batch and cellular companies were similar to the results of the MSA in the batch company conducted by Prasetyo, Belleville, and Ozarska.¹¹ Therefore, it was concluded that a corrective action for the wood recovery rate assessment system applied in the furniture manufacturing process is not required.

Conclusions

1. Comparing two furniture production systems, batch and cellular production systems, there was a significant difference in cumulative wood recovery rates between these systems.
2. Both the mass and volume methods could be used to assess the wood recovery rate at four stations: the resawing and edging, surface-planing, thickness-planing, and end-trimming stations, as both methods were not significantly different in the wood recovery rates, including the standard deviation. The mass method could be used to measure the wood recovery rate at all furniture manufacturing stations.
3. Based on species, the average individual and cumulative wood recovery rates of furniture manufacturing resulted in a significant difference at the resawing and edging station. Based on product dimension, a significant difference in the average individual and cumulative wood recovery rates only occurred at the resawing and edging station, where for both parameters, large-dimension products recorded higher wood recovery level than small-dimension products.
4. The wood recovery rates at the first four stations (i.e., the resawing and edging station, surface-planing, thickness-planing, and end-trimming stations) were mostly influenced by species, the quality of sawn timber, and cutting bills (component/product dimension or design). Meanwhile, the wood recovery at each station after the first four stations (e.g., mortizing, molding, carving, gluing, and jointing stations) were influenced by product dimension and product design.
5. Based on the MSA, both the volume and mass methods for the wood recovery rate measurement were applicable, reproducible, and repeatable because the percentage contributions of the variance component of the gage R&R for both methods were smaller than for the part variation. However, the interaction between the system and operator of the volume method should be considered because the wood recovery rate measurement system and the interaction between the system and operator were significant. Ultimately, the mass method was the most acceptable system.

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