A Proposed Method and Its Development for Wood Recovery Assessment in the Furniture Manufacturing Process

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A proposed method for assessing wood recovery involves application of a machining station approach with volume and mass measurements. A medium wood furniture company located in Jepara, Indonesia was selected to develop the method. Batch measurements of the inputs and outputs for different types of indoor-furniture products at every station were collected and analysed. For the volume method, three dimensions were measured on each specimen: the length, width, and thickness. For the mass method, the specimens were weighed before and after each processing station using a balance. Based on the mass method, the average total wood recovery rate was 26.2% ± 2.3%. For individual products and per station, the significant difference in the wood recovery rate occurred only at the resawing and edging, and trimming stations. The relationship between the teak quality, product dimensions, and type of finish was significantly different, where A-quality teak, large dimensions, and polyurethane finish resulted in a higher wood recovery rate. Both methods were reliable because of insignificant differences in the wood recovery rates. However, the mass method was more efficient and practical. The proposed protocol using the mass method is a suitable and effective system because the contribution of the variance component of the method was 2.71%.

Keywords: Wood recovery; Wood furniture manufacturing; Contribution of variance component; Station approach; R-chart by operator; Indonesia

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INTRODUCTION

Wood recovery can be defined as the quantity of wood utilised for manufacturing products divided by the quantity of products generated in a year (USDA 2014), while yield is an efficiency metric of wood converting operations by deviding useful wood parts to rough sawn timber (Mitchell *et al.* 2005). In mill applications, wood recovery is frequently described as the ratio between the lumber output and input. The wood recovery rate of a wood manufacturing company depends on how the wood is processed to maximise the product quantity and quality (Buehlmann *et al.* 2003). The wood recovery rate is the most commonly applicable efficiency measurement in sawmilling converting operations (Huber *et al.* 1985; Buehlmann *et al.* 2003; Missanjo and Magodi 2015).

The wood processing industry has continually been striving to evaluate wood recovery rates to enhance profits. Ultimately, improved wood recovery plays a major role in a successful wood manufacturing operation (Huber *et al.* 1985). Obtaining increased wood recovery is an economic strategy for minimizing the raw material expenditure (Buehlmann *et al.* 2011). It can lead to creating potential savings in production costs. Moreover, by increasing wood recovery, less raw material is required to generate the same quantity of products. Thus, it enhances the production capacity towards an optimal wood manufacturing operation (Buehlmann *et al.* 2003).

Two measurement methods are commonly used to quantify the wood recovery: volume and mass. In sawmilling, a volume basis is usually applied to measure the wood recovery (Fahey and Woodfin 1982; Keegan *et al.* 2010; Olufemi 2012; Olufemi *et al.* 2012). For pulp and paper processing, mass is frequently used for measuring the pulping recovery (Bowyer *et al.* 2007). For assessing the wood recovery rate in furniture manufacturing processes, some companies have developed methods to assess the recovery rate, but they are for internal use only; no standard method has yet been developed and designed as a published standard for wood recovery rate assessment. The methods need to be assessed and justified before being applied in a furniture production operation, including the measures, object measurements, measurement system, and reliability of the wood recovery rate data.

The wood recovery rate in wood processing operations is influenced by several factors, which include the cutting bill, wood quality, machinery, and production system. A cutting bill, which is described as the quality and quantity requirements based on the customer order, is the most important factor that affects wood recovery (Buehlmann *et al.* 2003). The relationship between the cutting bill and wood recovery is complex because the bill is determined by the required geometry, quality, and quantity of the wood components (Buehlmann 1998; Buehlmann *et al.* 1998; Buehlmann *et al.* 2003). The geometry characteristics relate to the lumber dimensions (Wiedenback and Araman 1995; Buehlmann 1998; Mitchell *et al*. 2005). The quality and quantity requirements correlate to the size and type of wood defects allowed, one-face or both-face quality requirements, and lumber grade (Cumbo 1999; Buehlmann *et al.* 2011). Wood quality can be defined as the combination of all of the wood characteristics that affect the value recovery chain and serviceability of the end products (Zhang 2003). A higher wood quality usually generates a higher wood recovery rate (Mitchell *et al.* 2005). The recovery rates for furniture production are also probably influenced by those factors, where the timber grade and species affect the wood recovery. Machinery can influence the recovery rate of wood processing by affecting the precision and accuracy during wood machining (ITTO 2014). Inappropriate maintenance of wood processing machinery notably can translate into low recovery rates during wood processing (Nainggolen *et al*. 2007b). Ultimately, poor production systems and untrained human resources can cause inefficiencies because they lower wood recovery rates. For instance, a failure in the wood processing technique and worker capacity to eliminate thoroughly unacceptable wood defects can result in a reduction in the wood recovery rates (Huber *et al.* 1985; ISWA 2009).

Studies of wood recovery during secondary wood processing are scarce compared with primary processing, and this is particularly evident in the furniture manufacturing industry. Furniture production consists of a series of wood machining processes, including rip-sawing, planing, cross-cutting, moulding, routing, mortising, gluing and jointing, sanding, and assembling (Ozarska 1998; Motsenbocker *et al.* 2005; Ozarska and Sugiyanto 2015). The processes are also associated with the complexity of the furniture production system, where the production flow and layout vary according to the furniture producer. Furniture production also employs many sophisticated furniture component manufacturing processes that create irregular shapes and sizes, such as moulding, routing, tenon and mortising, turning, and conventional hand carving. Production is exacerbated by many products requiring various ranges of different raw materials (Sabri and Shayan 2004). All of the aforementioned factors make it difficult to assess the wood recovery rate in the furniture manufacturing industry. For instance, a study conducted by Nainggolan *et al*. (2007a) in Indonesia, one of the top 20 largest wood furniture exporting nations worldwide (Globe 2016), mentioned that the wood recovery rate during furniture production is 38%. However, the report was not based on any standard, as the industry lacks a standard procedure to assess the wood recovery rate in furniture production. This case could be different to many furniture manufacturers worldwide, where the recovery rates are under continuous control and improvement. A volumetric calculation is commonly used to compute wood recovery rates for this type of production.

Several methods to enhance wood recovery during furniture production have been used and analysed to increase the wood recovery rate for primary processing operations, which utilise multiple rip-sawing and cross-cutting processes to produce parts with a specific size, wood quality standard, and quantity from rough sawn lumber (Thomas and Buehlmann 2007). However, the study by Thomas and Buehlmann (2007) was conducted at the primary processing stations only, and it did not cover the entire furniture production process, *i.e.* conversion from rough sawn timber to the finished product. Character-marked lumber, wood species, cutting bill requirements, lumber size, and dimensions have been analysed in conjunction with the use of rip-first rough mill simulation software and data banks to mimic real manufacturing processes to optimize the wood recovery rate in the studies by Wiedenback and Araman (1995), Buehlmann (1998), Buehlmann *et al.* (1998), Hamner *et al.* (2002), and Buehlmann *et al.* (2003, 2008). Again, these studies did not involve the whole furniture making process or machining stations.

A decrease in the availability of large diameter trees and an increasing demand for wood products is forcing wood processing manufacturers to utilise short rotation plantation trees to produce their products. Young plantation trees, such as a great proportion of juvenile wood with relatively small dimensions and uncertain wood properties, are characterised as having an inferior wood quality (Kojima *et al.* 2009; Ozarska 2009). By utilising these trees to manufacture high-value products, these characteristics require technically sophisticated facilities and advanced technologies (Ozarska 1998). Wood recovery as an efficiency measurement can then determine the conformity between the characteristics of young plantation timber and the wood processing facilities and technologies employed. When the wood processing technologies are incompatible with utilising young plantation timber, the processes might lower the wood recovery rate. Furthermore, a standard wood recovery rate assessment methodology could assist in determining the optimum wood utilisation as an environmentally sustainable way to achieve maximum added-value from forest resources.

The present study was part of a research project that attempted to develop specific efficiency metrics for assessing improvements in furniture production. Therefore, the aim of this study was to develop a simple and effective method to measure the wood recovery rate in the furniture manufacturing process. The specific objectives of this study were: (1) to develop a simple and effective method for assessing the wood recovery rate at every machining station, (2) to examine and compare methods that use two different measurement methods (volume and mass), and (3) to analyse the proposed methods using measurement gage analysis.

EXPERIMENTAL

Selection of the Wood Furniture Manufacturing Companies

Three representative medium-sized wood furniture manufacturing companies in the Jepara region of Central Java Province, Indonesia were randomly selected to conduct the wood recovery rate analysis. The criteria for company selection were that the company: 1) employed between 20 and 99 people as defined by the Indonesian Central Bureau of Statistics (BPS 2016); 2) produced all of the furniture in-house; 3) used plantation-grown timber; and 4) was willing to be part of the research project and implement future recommendations arising from the study. The production system, capacity, and use of common furniture raw materials, *Tectona grandis* in this case, was also considered in the selection process.

One of the three companies, subsequently called company A, was chosen for the development of a method to measure the wood recovery rate in the furniture manufacturing process, while the other two companies, B and C, will be considered for the upcoming validation of the proposed method.

Company A typically produces four containers per month of a wide variety of wood furniture products, which are equivalent to approximately 200 m^3 of wood. The company mainly exports their products to the Netherlands, Taiwan, and South Korea. The company employs a total of 63 full-time highly skilled furniture makers, has a production system based on the products ordered, and each worker produces a certain volume of a specific furniture product.

Wood Recovery Rate Assessment

The development of a method for measuring the wood recovery rate in the furniture manufacturing process was divided into three stages: planning, investigation of the current furniture production stages, and data collection.

Planning stage

The aim of the project was initially presented to production managers/supervisors and the plan to develop a wood recovery rate assessment method was considered. The objectives, stages of the assessment, and a detailed procedure on how the wood recovery rate data would be collected were also explained. A factory tour was then conducted so that the researchers could become familiar with the furniture production layout and material flow on the production floor. In the present study, the units that were measured (sawn boards and furniture components) were defined as specimens. Plans for specimen measurements and data collection were arranged on the production floor. The aspects that were considered consisted of a visual assessment of the production flow, production and worker scheduling, product specifications, machining processes, specimen measurements and data acquisition, manual and digital data recording, and photo and video documentation. Four researchers were involved in the present experimental study.

Investigation of the current furniture production stages

Three aspects of the production process were investigated before assessing the wood recovery, which were the production time, production flow, and auxiliary information related to the production system. The production time included identifying the current furniture production scheduling, type of furniture produced, processing time, and duration of furniture production. In an Indonesian furniture manufacturing context, understanding that scheduling of the workers is part of the production scheduling was inevitably important because producing a type of furniture product (cabinets, tables, chairs, *etc.*) requires a furniture maker with specific skills. Highly-skilled furniture makers are commonly referred to as contract workers, who have a duty and remuneration to accomplish a particular task and make a certain volume of a product within a specific timeframe. An investigation into the production time then informed the researchers about the starting time, research duration, and products assessed.

A total of eight products were examined: two types of bedside tables, two types of table tops, a side cabinet, a TV cabinet, a dining table, and a sofa frame (Table 1). The whole study from the planning stage to the data collection stage was conducted over seven days. The production flow determined the factory layout, placement and use of the machinery, and the stock area and its control. Each stage of the furniture manufacturing process was assessed. Detailed drawings of the furniture production and specimen flows were made, and included the position of the workers, specimen stacking before and after machining, and pathways of the workers and timber (Fig. 1).

Table 1. Specifications of the Furniture Products Examined at Company A

Type of Product	Dimensions (D/T x W x L) (cm)	Teak Quality Classes Used*	Type of Finish	Customer
Bedside table 1	45 x 48 x 55	B and C	Polyurethane	Taiwan
Table top 1	3 x 110 x 210	A and B	Polyurethane	Taiwan
Bedside table 2	55 x 49 x 55	B and C	Polyurethane	Taiwan
Side cabinet	60 x 45 x 200	A	Polyurethane	Indonesia
Table top 2	3 x 90 x 210	A and B	Polyurethane	Taiwan
TV cabinet	45 x 77 x 85	A	Teak oil	The Netherlands
Dining table	74.5 x 100 x 240	A	Teak oil	The Netherlands
Sofa frame	71 x 82 x 144	B and C	Polyurethane	Taiwan

D: depth; T: thickness; W: width; L: length; *as classified by the standard of company A; A: highest quality (no knots, no sapwood, no decay, no oil canal, and uniform colour); B: medium quality (≤ 45-mm knots, small proportion of sapwood (≤ 20%), no decay, small oil canal, and non-uniform colour); C: lowest quality (allows knots, big proportion of sapwood (> 20%), decay, oil canal, and non-uniform colour)

Data collection

The material assessment included the quality, dimensions, and moisture content of the sawn boards utilised for the wood recovery rate study. A visual assessment of each board quality was conducted based on the Indonesian National Standards SNI 7539.1:2010 (2010) and SNI 7537.2:2010 (2010). The moisture content was assessed using the Australian and New Zealand standard AS/NZS 4787:2001 (2001) with a standard resistance moisture meter.

Each individual component was marked and tracked along the manufacturing process. At the resawing and edging station, the faces and edges of the specimens were marked if further sampling was anticipated for smaller sections of the specimens. At the surface planing, thickness planing, and sanding stations, only the tips of the specimens were marked. At the gluing and jointing station and assembling station, the visible faces and tips were marked to anticipate the jointing and assembling processes generating new dimensional specimens.

A minimum of 30 specimens were measured per station. Batch measurements involved measuring a number of specimens machined together at each processing station, which were then collectively conveyed to the next station (Fig. 1). The inputs and outputs were measured for each processing station. However, from the gluing and jointing station to the final stations, the number of specimens decreased as some of the specimens were jointed to become new specimens.

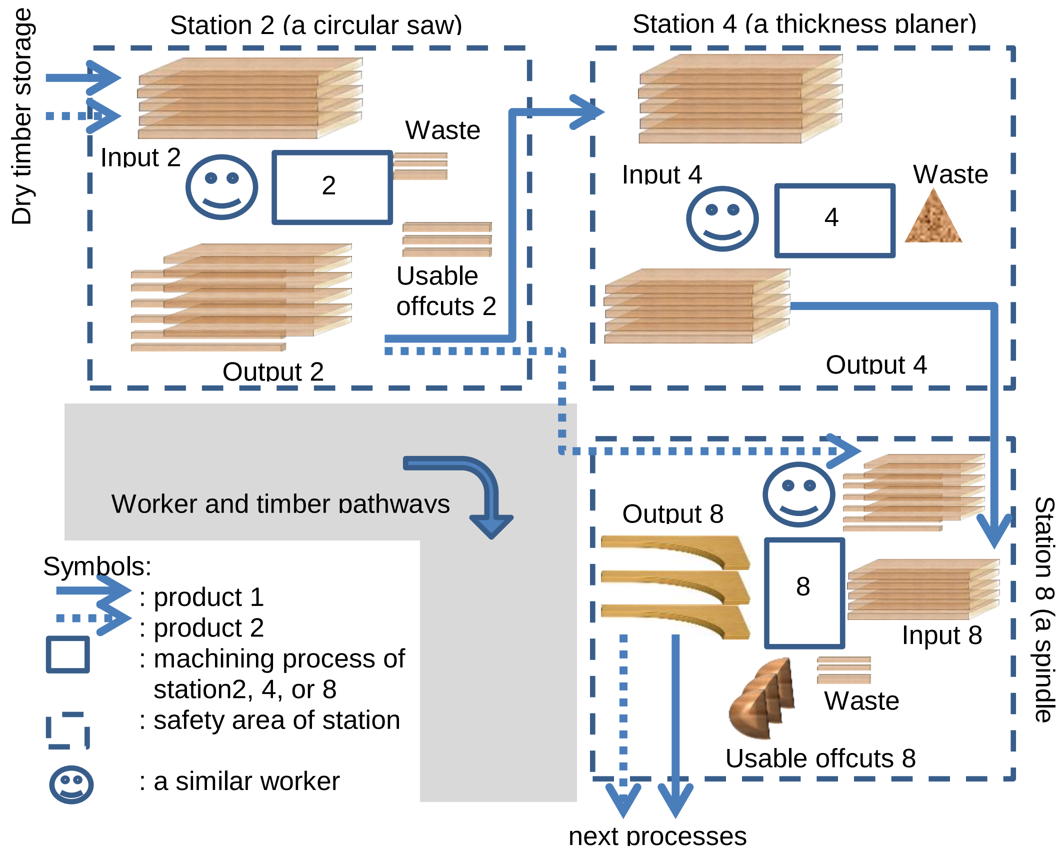


Fig. 1. Flow of the wood recovery rate measurement of the products at stations 2 (circular saw), 4 (thickness planer), and 8 (spindle moulder)

The production layout in company A started at the resawing and edging station, and was followed by the surface planing, thickness planing, and end trimming stations (Fig. 2). The machines used at the resawing and edging station included a small band saw and two circular saws. From this station, the dry rough sawn timber that came from storage was converted into pieces of furniture specimens based on a cutting bill. The use of a small band saw and the circular saws depended on the grade and dimension of the sawn timber, wood defect types, and cutting bills. The specimens produced were then processed at the surface planing station, where two or four sides of the specimens were evenly planed at an angle perpendicular to the cutting edge. True square specimens were then planed by the thickness planers to generate a consistent or similar thickness. The end trimming station cut the specimens to similar lengths. However, specimens that were used for creating a large number of furniture components using a gluing and jointing process were not cut at the end trimming station, but were directly moved to the routing or moulding processes.

The router was most commonly used as a plunging machine or a router edge to make hollows, curves, and varied corners. To make a mortise and tenon joint to connect two furniture specimens, mortising and tenon stations were used. A mortise produces a cavity, while a tenon produces a tongue. To produce long joints and decorative edges and to bend shapes on the furniture specimens, a moulding process was used. Gluing and jointing were mostly used to produce large scale furniture specimens and merge different furniture components. The trimming station was generally used to cut the furniture specimens to the desired lengths using circular and hand saws before the assembly of the specimens. The sanding station was the final stage of the furniture making process before the specimens were sent to the finishing department.

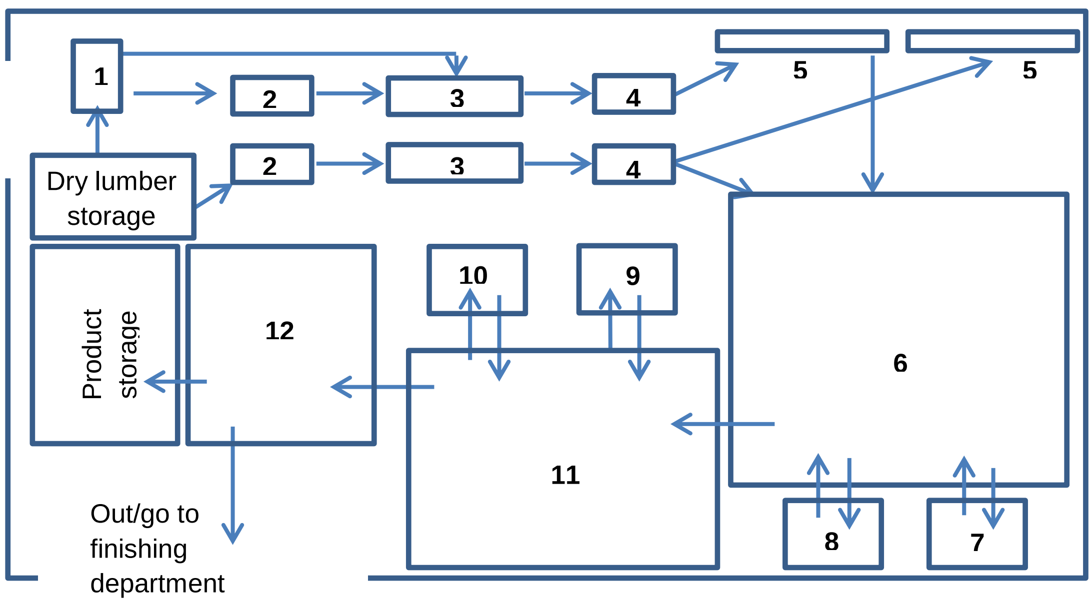
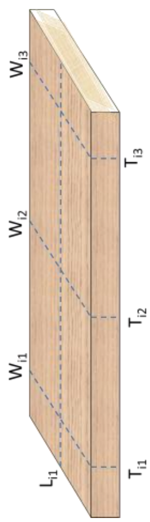
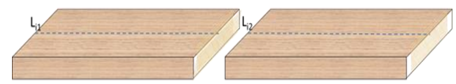
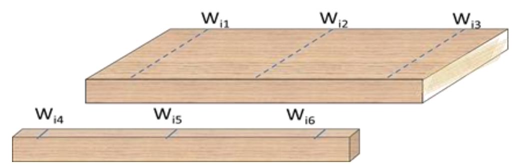
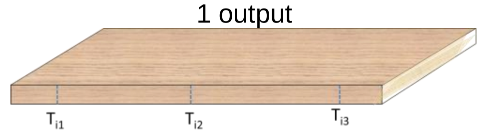


Fig. 2. Furniture production layout: 1: edging; 2: resawing; 3: surface planing; 4: thickness planing; 5: end trimming; 6: routing and assembling; 7: tenon and mortising; 8: moulding; 9: gluing; 10: trimming; 11: jointing and assembling; and 12: sanding

Two methods were used for measuring the inputs and outputs at each station, which were the volume and mass measurement methods. For the volume method, three dimensions were measured on each specimen, which were the length (*L*), width (*W*), and thickness (*T*). The *L* was measured at one position in the middle of the widest section of a specimen. The *W* and *T* were measured at three positions, *i.e.* a measurement at each end and another in the middle. A digital veneer calliper (± 0.01 mm) was used to measure the *T*, while a measuring tape (± 0.1 cm) was used for measuring the *L* and *W*. The mass method was conducted using a standard balance (± 0.1 kg), and the specimens were weighed before and after each processing station. When the output measurements were done to quantify the processed specimens, the usable offcuts were collected separately and also measured if they were further utilised. The procedure for quantifying the inputs and outputs for different scenarios is presented in Table 2.

A cutting bill, including the specification of a product, is a guide to understanding the number of furniture specimens measured, including the sizes and shapes. It is related to the type of measurement employed, which was either the volume method using callipers and measuring tapes or the mass method using a balance.

Table 2. Procedure for Quantifying the Output from the Input

Input	Station	Output Scenario	Measurement
	Edging and resawing (1 & 2), and end trimming (5)	2 outputs 	*L*
		2 outputs and 1 offcut 	*L*
		1 output and 1 offcut 	*W*
	Surface planing (3) and thickness planing (4)	1 output 	*W* and *T*
	Routing (6), tenon and mortise (7), moulding (8), gluing and jointing (9), trimming (10), assembling (11), and sanding (12)		Weighing specimens
L: length; *W*: width; *T*: thickness			

The formulas for calculating the recovery rate of a specimen using the volume and mass methods at each processing station are as follows (adapted from USDA 2014),

$$R_{v\ 1,2,3,\ldots,n} = \frac{Volume\ output\ S_{1,2,3,\ldots,n}}{Volume\ input\ S_{1,2,3,\ldots,n}}\ x\ 100 \tag{1}$$

$$R_{w\ 1,2,3,\ldots,n} = \frac{Mass\ output\ S_{1,2,3,\ldots,n}}{Mass\ input\ S_{1,2,3,\ldots,n}}\ x\ 100 \tag{2}$$

where R_v is the recovery rate using the volume method (%), R_w is the recovery rate using the mass method (%), and $S_{1,2,3,\ldots,n}$ is a specimen (1, 2, 3, *etc.*).

The calculations of the average recovery rate of *n* specimens using the volume and mass methods at one processing station are given by Eqs. 3 and 4, respectively,

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

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

where $R_{Av\,V}$ is the average recovery rate using the volume method (%), $R_{Av\,W}$ is the average recovery rate using the mass method (%), and n is the number of specimens.

The calculation of the overall rate of all of the processes using the volume and mass methods with the assumption that the furniture manufacturing stations included edging (e), end trimming (c), planing (p), routing (r), and sanding (s) used the following equation (USDA 2014):

$$R = R_e \; x \; R_c \; x \; R_p \; x \; R_r \; x \; R_s \tag{5}$$

where R is the overall recovery rate of the furniture manufacturing process (%).

All of the data collected was analysed using SigmaXL software supplied by SigmaXL Inc. (V.8, Kitchener, Canada) for graphical and statistical analysis, and measurement systems analysis (MSA).

RESULTS AND DISCUSSION

Quality assessments were conducted on dry rough sawn timber based on Indonesian National Standards (SNI 7537.2:2010 2010; SNI 7539.1:2010 2010) and an Australian and New Zealand standard (AS/NZS 4787:2001 2001). However, the quality of the sawn timber did not meet the criteria of SNI 7539.1:2010 (2010). This was because the teak logs were purchased by a saw miller and converted into rough sawn timber without applying the SNI standard. The logs were purchased from different sources, such as well-managed plantations, agroforestry, and farms. Additionally, the customer requirements did not rely on the SNI standard. For the above reasons, this case is incomparable with recovery studies in furniture companies conducted by Wiedenback and Araman (1995), Buehlmann (1998), Buehlmann *et al.* (1998), Hamner *et al.* (2002), Buehlmann *et al.* (2003), Buehlmann *et al.* (2008), and Thomas and Buehlmann (2007). The cited authors assessed and improved the wood recovery rates in primary processing stations of furniture manufacturing using graded sawn timber, which was based on National Hardwood Lumber Association (NLHA) standard. The graded sawn timber generated better recovery rates and the ease of wood recovery assessment, monitoring, and improvement. The teak quality was therefore substantially derived from the customer requirements to ease categorising in this paper and selecting sawn timber for each product specification. Three classifications of teak quality were consistently used as the in-house specifications by company A to fulfil the customer requirements: quality A (no knots, no sapwood, no decay, no oil canal, and uniform colour); quality B (≤ 45-mm knots, small proportion of sapwood (≤ 20%), no decay, small oil canal, and non-uniform colour); and quality C (allows knots, big proportion of sapwood (> 20%), decay, oil canal, and non-uniform colour). When selecting the sawn timber according to the cutting bill, some combinations of different teak quality classes were applied to optimise the recovery. The moisture content of the timber was assessed based on the company standard (≥ 12% and ≤ 16%) or customer requirements regarding the final destinations of the products.

Wood Recovery Assessment of the Furniture Manufacturing Process

Table 4 shows the wood recovery rate assessment of the eight types of furniture products at every station using the mass and volume methods. The wood recovery rates for each method were determined based on the individual station recovery rates per product and the total wood recovery rate, which resulted in the determination of the wood recovery rates for all of the stations employed per product. The method for measuring the wood recovery rate in the furniture manufacturing process applied a machining station approach. The wood recovery rate was measured at every station, which was done by following the production flow of a type of furniture product. Ultimately, all of the selected products, which were manufactured at all of the stations, were involved.

A variance analysis was also performed to compare the wood recovery rates of individual products and stations (Table 3). To compare individual products, several parameters were derived from the product specifications: 1) teak quality classes used for each product (A, A-B, and B-C); 2) product dimensions: small (bedside table 1, bedside table 2, and TV cabinet) and large (table top 1, table top 2, side cabinet, dining table, and sofa frame); and 3) type of finish (polyurethane and teak oil). A multi-vari chart and two statistical analyses (*t*-test and analysis of variance (ANOVA)) were applied, which were then followed by the advanced post HOC 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, and trimming stations.

The resawing and edging process generated the lowest wood recovery rate of all of the stations no matter which product was manufactured, and ranged from 47.9% ± 14.5% to 79.0% ± 11.7% (Table 4). When looking at the individual products, the recovery rates at the resawing and edging station varied, and the bedside table products had the lowest rates of recovery (53.5% ± 9.2% to 56.9% ± 7.5%). The low levels of recovery were caused by the small dimensions, which were 45 cm x 48 cm x 55 cm and 55 cm x 49 cm x 55 cm, and the polyurethane finish, which required a mix of teak qualities (B and C). This relationship resulted in the significantly lowest wood recovery rate (*F*-value = 91.68) compared with the relationships between the large dimensions and teak oil, large dimensions and polyurethane, and small dimensions and teak oil (Table 3). The TV cabinet and dining table products had similar recovery rates (58.3% ± 15.8% to 59.9% ± 15.2%), while the table top and side cabinet products had higher recovery rates (63.3% ± 4.7% to 79.0% ± 11.7%) compared with the other products. These products had large dimensions and were made using quality A teak with a polyurethane finish. This interaction of three parameters resulted in a significantly higher recovery rate than the other interactions (*F*-value = 31.06). Although the sofa frame product also had large dimensions (71 cm x 82 cm x 144 cm), the product did not have the same recovery rate as the other large-dimension products (47.9% ± 14.5% to 48.6% ± 12.9%) because it was produced using mixed teak qualities (B and C) and was finished with polyurethane (*F*-value = 13.20). Despite the fact that the resawing and edging station is an initial machining station, the low wood recovery rate at this station was influenced by the removal of undesirable edges and defects, such as knots, sapwood, resin canals, and brittle heart. This result corresponded to Mitchell *et al.* (2005) and Wiedenback (2001), who stated that the considerations of the initial machining operations are related to the dimensions/design and quality of the utilised timber.

The surface planing station achieved wood recovery rates for all of the products that were between 90.3% ± 2.7% and 96.4% ± 2.2%. This meant that when machining all of the furniture specimens at the surface planing station, the wood recovery rate was between 90.3% ± 3.7% and 96.4% ± 2.2%. This station did not remove a high volume of wood from each product because it only addressed the surface of two or four sides of a specimen to provide a square finish before it was processed by a thickness planer. The rate of wood recovery at the thickness planing station was between 74.6% ± 12.9% and 90.9% ± 8.5% for all of the products. The wood recovery rate for all of the products at this station was critical as it could be influenced by the cutting bill and selection of sawn timber with an appropriate thickness. Therefore, the calculation of the thickness allowance from log conversion and drying processes was a major factor for limiting wood removal at the thickness planing station. The wood recovery rate of the end trimming process was between 71.9% ± 16.6% and 97.2% ± 2.6% for all of the products.

After the first four machining stations, the remaining machining operations formed the specimens into various furniture components using the routing, mortising, moulding, gluing and jointing, trimming, assembling, and sanding stations. The use of these stations depended on the furniture component type; therefore, not every station was involved in producing a product. The wood recovery rate at the routing station was between 98.4% ± 0.3% and 99.2% ± 0.1%. The routing station was required to produce the bedside table, table top, and dining table products, but was not required for producing the cabinet products. The wood recovery rate of the routing station was relatively similar for all of the products, and was a representation of all of the furniture manufacturing stations.

Table 3. Analysis of the Wood Recovery Rate According to the Product Specification Parameters and Station

Parameter	Statistical Analysis Method	Station				
		Resawing and Edging			Trimming	
		n	*t*/*F*	Subset group and Tukey's HSD test	*n*	*t*/*F*
Teak quality classes used (TQ)	One-way ANOVA (*F*)	61	48.87**	A^{A}; AB^{B}; BC^{B}; Tukey's HSD = 6.22	N.S.	N.S.
Product dimension (PD)	t-test (*t*)	90	-8.29**	N.A.	30	-11.26**
Type of finish (TF)	t-test (*t*)	60	-5.09**	N.A.	N.S.	N.S.
TQ x PD	One-way ANOVA (*F*)	60	31.06**	Large dimensions: quality A^{A}; quality AB^{A}; quality BC^{B}; Tukey's HSD = 8.81	N.S.	N.S.
TQ x TF	One-way ANOVA (*F*)	60	13.20**	Polyurethane: quality A^{A}; quality AB^{A}; quality BC^{B}; Tukey's HSD = 7.49	N.S.	N.S.
PD x TF	One-way ANOVA (*F*)	60	91.68**	Large dimension and teak oil^{A}; large dimension and polyurethane^{B}; small dimension and teak oil^{C}; small dimension and polyurethane^{C}; Tukey's HSD = 7.95	N.S.	N.S.
TQ x PD x TF	One-way ANOVA (*F*)	30	31.06**	Large dimension and polyurethane: quality A^{A}; quality AB^{A}; quality BC^{B}; Tukey's HSD = 8.81	N.S.	N.S.

**significant at an α of 0.01 according to the Mann-Whitney *t*-test (*t*); for a given test, values followed by the same letter in the subset group did not differ significantly (α = 0.01) according to the one-way ANOVA (*F*); N.A. = not applicable; N.S. = not significant

Table 4. Total and Individual Wood Recovery Results (%) per Product Using the Mass and Volume Methods

Product	Method		Station										
			Resawing and Edging	Surface Planing	Thickness Planing	End Trimming	Routing	Mortising	Moulding	Gluing and Jointing	Trimming	Assembly	Sanding
Bedside table 1	Mass	Individual	56.9[A] 7.5[B] 30[C]	90.3 3.7 30	88.5 3.8 30	71.9 16.6 30	98.5 0.4 30	94.4 4.6 30	91.4 3.1 30	100 0 30	69.7 1.5 30	100 0 8	N.M.
		Total	56.9	51.4	45.5	32.7	32.3	30.4	27.8	27.8	19.4	19.4	N.M.
	Volume	Individual	56.0 8.8 30	90.9 3.8 30	86.6 3.6 30	73.1 16.8 30	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
		Total	56.0	50.9	44.1	32.3	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
Table top 1	Mass	Individual	65.0 5.7 30	94.6 2.7 30	88.8 2.7 30	N.A.	98.4 0.3 30	N.A.	N.A.	99.7 0.1 12	95.9 0.5 12	100 0 12	N.A.
		Total	65.0	61.5	54.6	N.A.	53.8	N.A.	N.A.	53.6	51.4	51.4	N.A.
	Volume	Individual	63.3 4.7 30	96.4 2.2 30	87.8 2.2 30	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
		Total	63.3	61.0	53.6	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
Bedside table 2	Mass	Individual	53.5 9.2 30	92.3 5.6 30	84.9 10.4 30	72.8 6.9 30	96.4 3.5 30	N.A.	83.3 10.8 30	92.1 5.6 30	88.7 2.9 30	100 0 8	N.M.
		Total	53.5	49.4	41.9	30.5	29.4	N.A.	24.5	22.6	20.0	20.0	N.M.
	Volume	Individual	54.6 9.4 30	94.6 5.1 30	86.2 9.7 30	70.2 6.5 30	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
		Total	54.6	51.7	44.5	31.3	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
Side cabinet	Mass	Individual	69.7 13.5 30	92.4 4.9 30	80.0 11.0 30	97.2 2.6 30	N.A.	N.A.	N.A.	N.A.	N.A.	100 0 12	N.A.
		Total	69.7	64.4	51.5	50.1	N.A.	N.A.	N.A.	N.A.	N.A.	50.1	N.A.
	Volume	Individual	77.9 14.6 30	92.6 4.8 30	79.8 14.0 30	89.9 2.9 30	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.

		Total	77.9	72.1	57.6	51.8	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
Table top 2	Mass	Individual	79.0 11.7 30	N.M.	74.6 12.9 30	N.A.	99.0 0.1 30	N.A.	N.A.	96.0 0.8 15	99.5 0.2 15	100 0 15	N.A.
		Total	79.0		58.9	N.A.	58.3	N.A.	N.A.	56.0	55.7	55.7	N.A.
	Volume	Individual	75.3 12.3 30	N.M.	83.8 11.8 30	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
		Total	75.3		63.1	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
TV cabinet	Mass	Individual	58.3 15.9 30	94.8 3.9 30	88.3 11.7 30	87.9 6.5 30	N.A.	93.6 5.1 30	N.A.	94.8 0.3 30	N.A.	100 0 10	94.8 0.3 10
		Total	58.3	55.2	48.8	42.9	N.A.	40.1	N.A.	38.0	N.A.	38.0	36.1
	Volume	Individual	59.0 15.8 30	91.7 3.9 30	90.9 8.5 30	92.0 5.2 30	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
		Total	59.0	54.1	49.2	45.3	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
Dining table	Mass	Individual	59.9 15.2 30	95.0 1.6 30	89.2 6.8 30	N.A.	99.2 0.1 30	80.0 10.8 30	N.A.	98.6 0.2 8	N.A.	100 0 8	N.A.
		Total	59.9	56.9	50.7	N.A.	50.3	40.3	N.A.	39.7	N.A.	39.7	N.A.
	Volume	Individual	58.7 15.3 30	96.9 1.9 30	88.5 6.5 30	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
		Total	58.7	56.9	50.3	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
Sofa frame	Mass	Individual	48.6 12.9 30	94.2 3.7 30	90.2 6.0 30	87.9 6.0 30	95.2 2.2 30	95.1 3.3 30	N.A.	N.A.	N.A.	100 0 8	N.M.
		Total	48.6	45.8	41.3	36.3	34.6	32.9	N.A.	N.A.	N.A.	32.9	N.M.
	Volume	Individual	47.9 14.5 30	95.6 3.9 30	90.4 6.1 30	86.7 6.6 30	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
		Total	47.9	45.8	41.4	35.9	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.

N.A. = not applicable; N.M. = not measured; A = average wood recovery rate (%); B = standard deviation; C = number of specimens measured

Table 5. Average Total Wood Recovery Rate (%) and Individual Wood Recovery Rates for All of the Products (%) per Station

Method		Station										
		Resawing and Edging	Surface Planing	Thickness Planing	End Trimming	Routing	Mortising	Moulding	Gluing and Jointing	Trimming	Assembly	Sanding
Mass	Individual	61.5 [A] 17.3 [B] 240 [C]	93.4 6.1 210	87.2 12.5 240	83.6 12.1 150	97.8 1.2 180	90.8 8.2 120	87.4 9.4 60	96.5 3.5 125	88.5 10.6 57	100 0 81	94.8 0.3 10
	Total	61.5	57.4	50.0	41.8	40.9	37.1	35.8	31.7	27.7	27.7	26.2
Volume	Individual	61.6 18.3 240	94.1 5.9 210	87.2 12.2 240	82.4 12.1 150	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
	Total	61.6	58.0	50.5	41.6	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.

A = average wood recovery rate (%); B = standard deviation; C = number of specimens measured, N.A. = not applicable

The mortising station had a wood recovery rate between 80.0% ± 10.8% and 95.1% ± 3.3%, and generated the bedside table, TV cabinet, dining table, and sofa frame products. A wood recovery rate between 83.3% ± 10.8% and 91.4% ± 3.1% was determined for the moulding station. The wood recovery rate at the gluing and jointing station ranged from 94.8% ± 0.3% to 100%. All of the products required the gluing and jointing station, except for the side cabinet and sofa frame products. The trimming station had a wood recovery rate that ranged from 69.7% ± 1.5% to 95.9% ± 0.5%. The wood recovery rate for the individual products at the trimming station varied significantly, where the large products had higher wood recovery rates compared with the small products (t-value = -11.26). This was determined from the wood recovery rates from the bedside tables and table tops. The wood recovery rate of the assembling process was 100% because there was no removal of wood during this stage. The wood recovery rate at the sanding station was 94.8% ± 0.3%, which was recorded from the production of the TV cabinets.

The total percentages of the wood recovery rates of the bedside table 1 and bedside table 2 products were 19.4% and 20.0%, respectively. Manufacturing of bedside table 1 involved ten stations, while bedside table 2 manufacturing involved nine stations. These rates were the lowest total wood recovery rates among all of the products examined, and these products were made from teak qualities B and C. These were also classified as small products. Another product made with the same teak qualities, but had larger dimensions than the bedside tables, was the sofa frame, where the wood recovery rate was 32.9% and involved seven stations. The wood recovery rates of the table top 1, table top 2, and side cabinet were 51.4%, 55.7%, and 50.1%, respectively. These products were manufactured using teak quality A. Interestingly, although the TV cabinet and dining table products were produced using teak quality A, the wood recovery rates of these products were lower than those for the table top and side cabinet products, which were 38.0% and 39.7%, respectively. This was because the recovery rates of the TV cabinets and dining tables at the resawing and edging station were lower, and were similar to other lower-recovery products.

An Anderson-Darling test, test of equal variance, and two-sample t-test were performed to test the difference between the wood recovery rates measured by the volume and mass methods. When the data was normal, whether the variance was equal or non-equal, a two-sample t-test was applied. For the non-normal data and when the variance was equal, a two-sample Mann-Whitney test was applied. When the variance was not equal for the non-normal data, the Kruskal-Wallis test was performed. The normal and non-normal data were analysed using histograms and descriptive statistics.

There was no significant difference ($P > 0.05$) between the volume and mass methods employed in the assessment of the wood recovery rate in the furniture manufacturing process. Both the mass and volume methods could be used for assessing the wood recovery rate at four stations: the resawing and edging, surface planing, thickness planing, and end trimming stations (see Table 3). At these stations, the rectangular shape of the furniture specimens was created and could be measured using the volume method. The volume method could not be applied when measuring specimens with curved, bent, rounded, or irregular shapes, or cavities. These were processed at the routing, mortising, moulding, gluing and jointing, and final trimming stations. The mass method could be used for measuring the wood recovery rate at all of the furniture manufacturing stations as this method can be applied to a wide variety of specimen shapes. When applying the mass method, the average time to weigh each specimen, capture the data, and record the data manually was 0.3 min. This process was very fast and efficient. When applying the volume method, 1.1 min was required on average to measure the L of a specimen at one point, and W and T at three points each. Only one data point per specimen was recorded using the mass method, while seven data points were recorded using the volume method. The seven data points could be 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, were not significantly different. Using scanning or sensor technologies for assessing dimension to calculate the wood recovery rate could be applied (Cumbo 1999), but it requires substantial capital investment for an Indonesian small-medium furniture making enterprises. Ultimately, considering the pace and efficiency of the data collection for measuring the specimens manually during active production processes, it was concluded that the mass method is more suitable than the volume method.

When measuring the inputs and outputs to assess the wood recovery rate at a station, apart from the processed specimens, usable offcuts were also considered and measured. This allowed for the examination of the wood recovery rates of the usable offcuts kept from previous processes. Therefore, these examination rates could increase the wood recovery rate itself.

The average total wood recovery rate for the 11 stations in company A was 26.2%, which was based on the mass method (Table 5). This was lower than the results of the previous research conducted by Nainggolan *et al*. (2007a) in Indonesia, which stated that the wood recovery level in the Indonesian furniture manufacturing industry is 38%. However, that study did not explain the method used for assessing the wood recovery rate. The resawing and edging, thickness planing, and end trimming stations recorded lower individual wood recovery rates than the remaining processes, which were 61.5% ± 17.3%, 83.6% ± 12.1%, and 87.2% ± 12.5%, respectively. These lower results for the average total wood recovery rates were followed by wood recovery rates at the moulding and trimming stations that were 87.4% ± 9.4% and 88.5% ± 10.6%, respectively. Comparing the average total and individual wood recovery rates for the first four stations, both the mass and volume methods measured wood recovery rates with the same standard deviation. The results were also similar to the overall and individual wood recovery rate results per product (Table 3), which revealed no significant differences between the volume and mass methods.

A furniture production system involving a different number of furniture making stations and various products might result in various wood recovery rates. Therefore, the number of stations and products used could change the recovery rates between different furniture companies. The wood recovery rate assessment applied in the batch production system, where a type of product is manufactured by a specific furniture maker, and continuous production system would also be different. These variables will be determined in upcoming validation studies conducted in other furniture companies. However, the methodology of the specimen measurement, data collection, and calculation of the wood recovery rate would principally be the same as that of the method proposed in this paper.

Analysis of the Wood Recovery Rate Assessment Method

An MSA was performed to validate the wood recovery rate assessment protocol. The analyser involved gage repeatability and reproducibility (R&R) analysis (crossed) and control charts for validating the proposed methods for the wood recovery rate assessment. The investigated parameters of the MSA 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.

For the volume method (Fig. 3), the wood recovery rate measurement system and the interaction between the system and operator were significant ($P < 0.05$). Meanwhile, the significant metric of the wood recovery rate measurement system for the mass method was the system itself ($P < 0.01$). This meant that when employing the volume method for assessing the wood recovery rate in the furniture making process, instead of the measurement system, the interaction between the system and operator had to be considered.

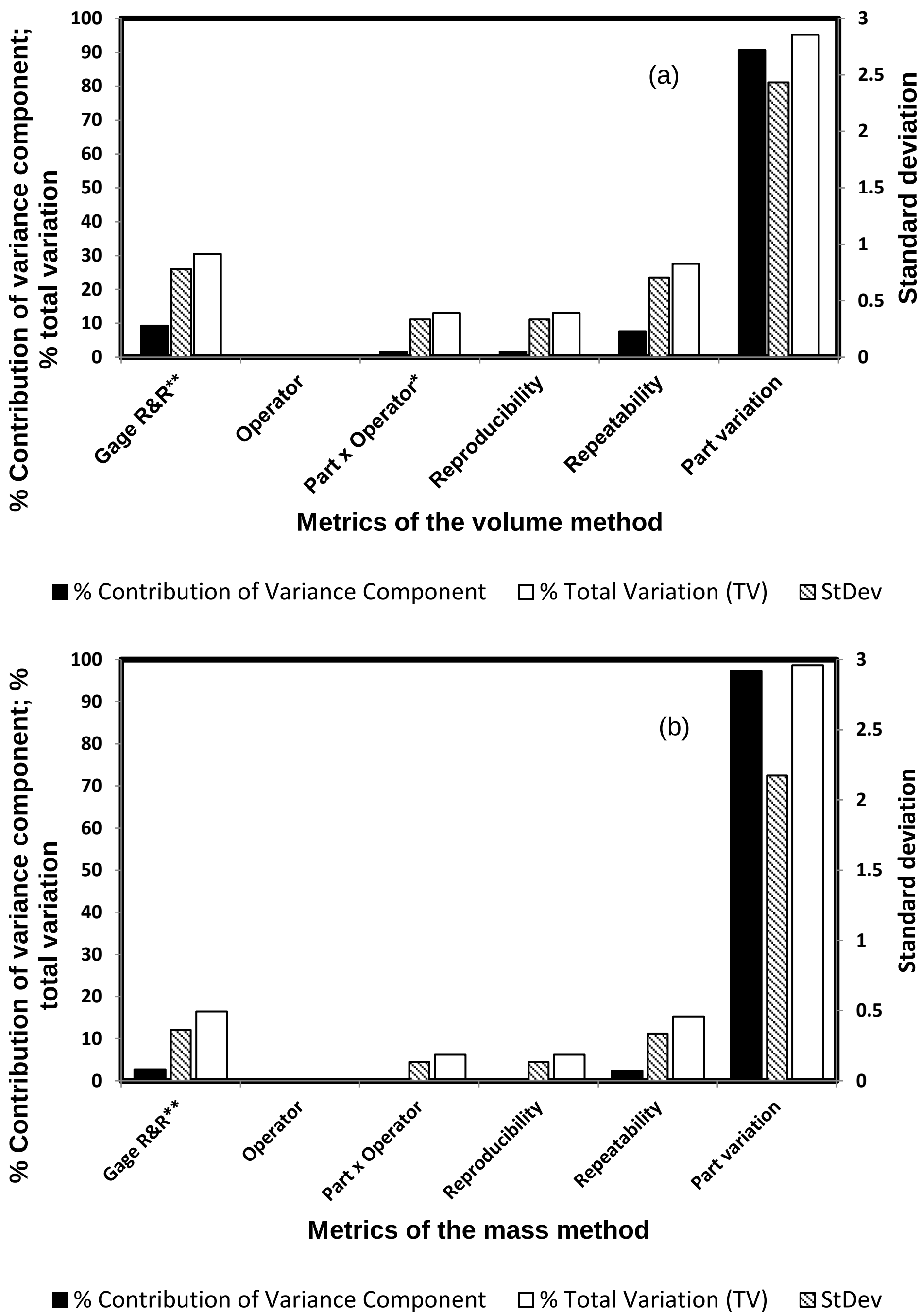


Fig. 3. Contribution of the variance component, percent total variation, and standard deviation of the wood recovery rate measurement metrics for both the volume (a) and mass (b) methods

According the Automotive Industry Action Group (2010) on gage standards, the contribution of the variance component of the volume method was 9.3%, where the method was categorised as a marginal system (< 10%). Meanwhile, the contribution of the variance component of the mass method was 2.7%, where the method was categorised as an acceptable system (< 4%). Both the volume and mass methods had low standard deviations (< 2.5). In the present study, the total variation was 10% to 30%.

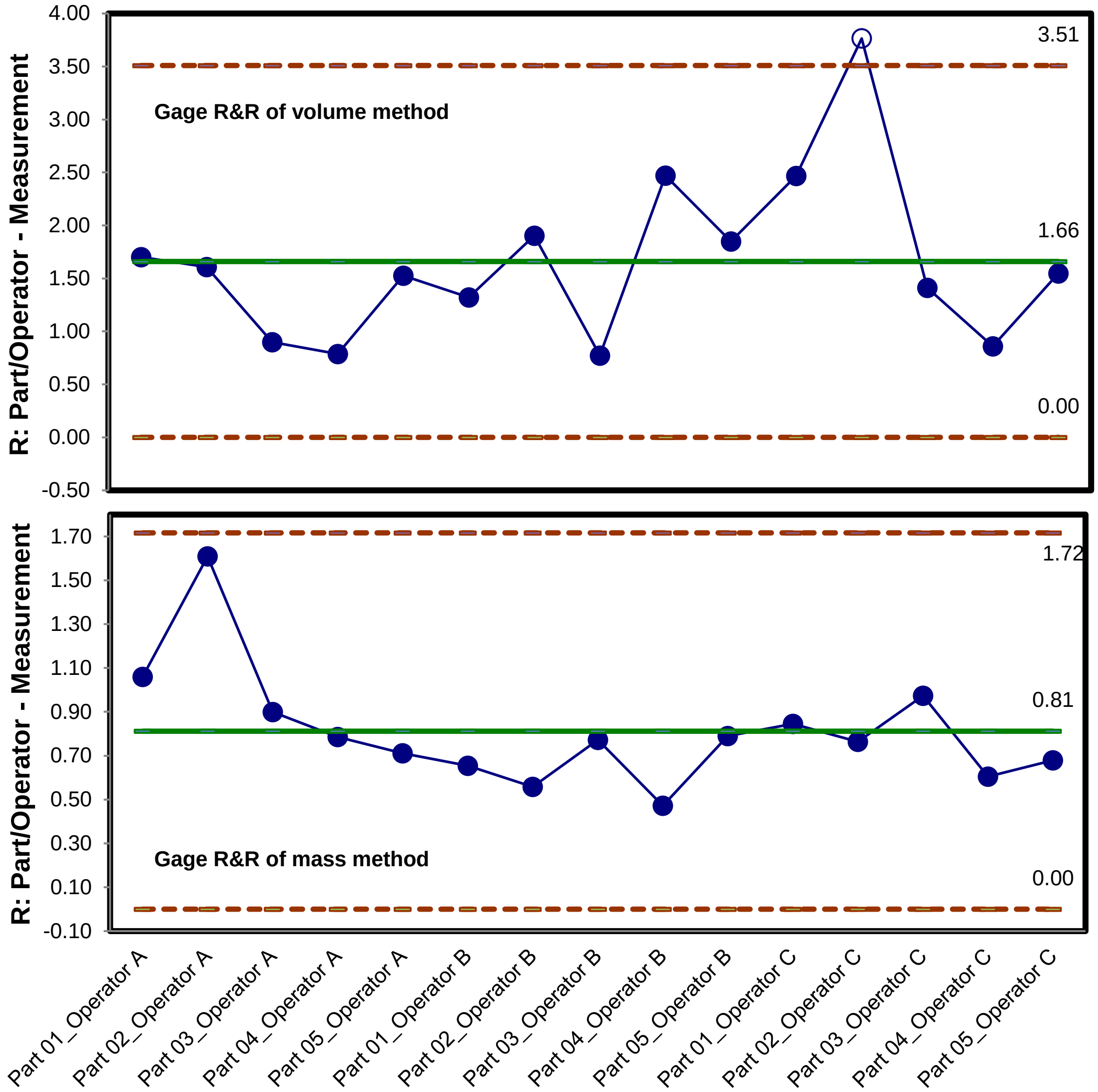


Fig. 4. R-chart by the operator of the wood recovery rate measurement system

When using the volume method, the contribution of the variance component (90.7%), total variation (95.2%), and standard deviation (2.4) of the part variation were larger than the contribution of the variance component (9.3%), total variation (30.5%), and standard deviation (0.8) of the gage variation (Fig. 3). Similar results were obtained when applying the mass method; the contribution of the variance component (97.3%), total variation (98.6%), and standard deviation (2.2) of the part variation were larger than the contribution of the variance component (2.7%), total variation (16.5%), and standard deviation (0.4) of the gage variation. This suggested that the gage system of the wood recovery rate measurement method using both the mass and volume methods in the furniture manufacturing process is reliable, reproducible, and repeatable. Therefore, it was concluded that a corrective action for the wood recovery rate assessment system is not required.

The consistency of the wood recovery rate measurement conducted by the operators is depicted in Fig. 4. When the operators assessed the wood recovery rate using the mass method, the differences between the largest and smallest measurements on each specimen measured by each operator were smaller (1.72) compared with those for the wood recovery rate assessment using the volume method (3.51). The average difference in the wood recovery rate measurements using the mass method was 0.81, while it was 1.66 for the volume method with a plotted point that exceeded the upper control limit. This means that the chart indicates an inconsistent measurement of the wood recovery using the volume method. Moreover, the variation in the wood recovery rate measurement among the specimens and operators using the mass method was smaller compared with that when using the volume method.

CONCLUSIONS

1. It was found that the application of a machining station approach, with the measurement of 30 specimens at each station, was a simple and effective protocol for wood recovery rate assessment during furniture production. When employing the mass and volume methods to measure the wood recovery rate, the most reliable and practical method was the mass method. The mass method could be used for measuring the wood recovery rate of a wide range of furniture specimen shapes across all of the furniture manufacturing stations if the whole process is under control. However, the volume method can provide information regarding the variation between and within each measured piece. The measurement process using the mass method was also very fast and efficient. Based on the statistical analysis, there was no significant difference between the volume and mass methods. However, the volume method could only be used for assessing the wood recovery rate at the first four stations, which were the resawing and edging, surface planing, thickness planing, and end trimming stations. For individual specimens and total wood recovery rates per product and per station, a significant difference in the wood recovery rate occurred only at the resawing and edging, and trimming stations, where the removal of a large proportion of wood was sometimes required.
2. Based on the mass method, the average total wood recovery rate for the 11 furniture manufacturing stations of company A was 26.2%. The resawing and edging, thickness planing, and end trimming stations recorded lower levels of individual wood recovery rates than the remaining processes, which was followed by the recovery rates of the moulding and trimming stations. The relationship between the teak quality, product dimensions, and type of finish was significantly different, where the quality A teak, large dimensions, and polyurethane finish resulted in a higher wood recovery rate compared with the other parameter combinations.
3. Based on the MSA, both the volume and mass methods for the wood recovery rate measurement were applicable, reproducible, and repeatable because the percent contributions of the variance component of the gage R&R for both methods were

smaller than for the part variation. However, the wood recovery rate measurement system and the interaction between the system and operator when using the volume method were significant. Therefore, the interaction between the system and operator should be considered. Meanwhile, the significant metric of the wood recovery rate measurement system using the mass method was the system itself. Furthermore, the mass method appeared to be the most acceptable system because the percent contribution of the variant components was between 1% and 4% (2.71%), which was in accordance with the Automotive Industry Action Group standards. Additionally, the R-chart by the operators from the mass method was more stable than the one from the volume method.

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