Evaluation of sawmilling and cross-laminated timber processing value chain integration

by

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Declaration

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Summary

Current high prices for CLT in South Africa are a deterrent to its adoption as a construction material. This prospect is further exacerbated by the predicted lumber shortages in the coming years. As such it is imperative to consider development of innovative, lower cost CLT manufacturing processes, underpinned by raw material optimization. This research investigated the integration of manufacturing of lumber and CLT with the aim of reducing the unit cost of CLT as a product.

Arguably the best potential for cost reduction of lumber is the increase of volume recovery during the sawmilling process. Two ways in which volume recovery increases can be achieved include the production of random width boards and increasing the wane allowance on boards. The objectives of this study were: (1) To evaluate the potential increase in volume recovery when an SA Pine sawmill include random widths and increased wane allowance in its sawing strategy (both random widths and increased wane products can potentially be used as raw materials for CLT manufacture), and (2) to investigate the effect of increased wane allowance on SA Pine CLT strength and stiffness performance.

To achieve the objectives; the research branched into three separate studies. Firstly, benchmarking of the Simsaw 6 sawmill software was performed to quantify the difference between simulated volume recovery and real-world volume recovery. Secondly, structured random widths (RW) and increased wane (IW) allowance scenarios were simulated to evaluate increase in volume recovery possible. Lastly, ten CLT panels of varying crosswise lamella wane surface area were manufactured and tested to destruction according to the American National Standards Institutes (ANSI) (2018) PRG-320 and EN 16351 (2015) specifications. This was done to determine whether increased wane allowance had an effect on CLT bending performance. Preparation of the panels closely mirrored commercial CLT fabrication.

Results from the sawmill benchmarking trial show that Simsaw 6 predicted real world sawmill yields. For small logs, the software overestimated log volume recovery by between 1,4% to 2,4% with a mean of 2,01% volume recovery overestimation. The software overestimated the real-world sawn logs volume recovery with between 1,3 to 3,7%, with a mean of 2,13% for large logs. For the small and large logs combined, the simulation results were on average 2,07% higher than real sawn results.

Increased wane allowance (IW) and increased wane allowance combined with random widths (IW+RW) showed significantly improved volume recoveries in all log classes. Using the maximum wane permitting scenario of (thickness =75%, width =50% and length =100%), the simulated volume recovery was interpolated to real-world sawmill volume recovery, as a weighted average of simulated yields. Maximum mean weighted volume recovery for a typical small-log sawmill was 63.5% for the increased wane combined with random widths scenario (IW+RW), followed closely by increased wane (IW) scenario at 61.5 % respectively. These volume recovery results indicate very high improvements compared to the current volume recoveries attained in typical sawmills in South Africa.

Ten sample CLT panels were manufactured and tested to failure and mechanical bending properties were determined. Prominent failure mode of the bending tests was the brittle tension failure, ensuing from the CLT bottom longitudinal layer. The measured knot properties on the middle section of the CLT panels were correlated with the MOE and MOE values; however, no significant correlation was noted. The experimental bending stiffness of each CLT panel was then compared with its predicted mechanical properties based on the shear analogy method for loads perpendicular to plane based on the global stiffness measurements. The comparisons between predicted and experimental results for the three wane groups, despite small sample size, show close similarity. Results from the severe wane category demonstrated that the inclusion of substantial wane percentage in CLT within the crosswise lamellas did not influence the bending stiffness of the CLT panel. A comparison between the experimental bending moment of the sample CLT panels and predicted bending moment of manufactured CLT panel was performed. The calculated experimental bending moment (FbS) results varied between 7.2 and 12.5 N. mm whilst the predicted bending moment for S5 CLT (FbS_{eff}) was 2.2 N.mm. Of the five severe wane panels, two had an FbS value lower than 10 N.mm/m. Of the five moderate and no-wane panels, none had values lower than 10 N.mm/m. It, therefore, seems as if the severe wane might have resulted in lower FbS values. If present, the magnitude of this effect still seems to be fairly small. It is likely that the lower bonding area due to gaps caused by wane was responsible for the perceived lower FbS values.

Overall, the results show a good indication of the potential use of wane edged boards in CLT production. CLT manufacturing with increased wane allowance boards resulted in high utilization of lower value lumber, therefore increased value extraction per single log. As attested by the successful design, testing and validation of the experimental work undertaken in this research, value chain integration seems to hold much potential to reduce the cost of CLT in South Africa.

Keywords: CLT; Simulation Optimization; Value addition; Random widths (RW); Increased Wane; Integration; Value Chain; Bending moment; Bending stiffness; Shear analogy model

Opsomming

Huidige hoë pryse vir CLT in Suid-Afrika is 'n afskrikmiddel vir die aanvaarding daarvan as 'n konstruksiemateriaal. Hierdie vooruitsig word verder vererger deur die voorspelde houttekorte in die komende jare. As sodanig is dit noodsaaklik om die ontwikkeling van innoverende, laerkoste CLT-vervaardigingsprosesse te oorweeg, ondersteun deur grondstofoptimalisering. Hierdie navorsing het die integrasie van vervaardiging van hout en CLT ondersoek met die doel om die eenheidskoste van CLT as 'n produk te verminder.

Waarskynlik die beste potensiaal vir kostevermindering van hout is die toename in volumeherwinning tydens die saagmeulproses. Twee maniere waarop volumeherwinnings-verhogings bewerkstellig kan word, sluit in die produksie van enige-breedte planke en die verhoging van die bastoelaag op planke. Die doelwitte van hierdie studie was: (1) Om die potensiële toename in volumeherwinning te evalueer wanneer 'n SA Dennesaagmeule enige breedtes en verhoogde bastoelaag in sy saagstrategie insluit (beide enige-breedtes en verhoogde basprodukte kan moontlik as grondstowwe vir CLT-vervaardiging dien), en (2) om die effek van verhoogde bastoelae op SA Den CLT-sterkte en styfheidsprestasie te ondersoek. Om die doelwitte te bereik het die navorsing in drie afsonderlike studies vertak. Eerstens is ‘n vergelykende studie van die Simsaw 6-saagmeulsagteware uitgevoer om die verskil tussen gesimuleerde volumeherwinning en werklike volumeherwinning te kwantifiseer. Tweedens is gestruktureerde enige-breedte (RW) en verhoogde bastoelae (IW) scenario's gesimuleer om toename in volumeherwinning moontlik te evalueer. Laastens, is tien CLT-panele met verskillende dwarslamella-oppervlakte vervaardig en getoets volgens die American National Standards Institutes (ANSI) (2018) PRG-320 en EN 16351 (2015) spesifikasies. Dit is gedoen om te bepaal of verhoogde bastoelae 'n effek op CLT-buigprestasie gehad het. Voorbereiding van die panele het die kommersiële CLT-vervaardiging weerspieël.

Resultate van die saagmeul vergelykingstoest toon dat Simsaw 6 werklike saagmeule-opbrengste goed voorspel het. Vir klein stompe het die sagteware stompvolume-herwinning met 1,4% tot 2,4% oorskat met 'n gemiddelde van 2,01% volume-herwinning-oorskatting. Die sagteware het die werklike herwinning oorskat met tussen 1,3 tot 3,7%, met 'n gemiddelde van 2,13% vir groot stompe. Vir die klein en groot stompe gekombineer was die simulasieresultate gemiddeld 2,07% hoër as werklike gesaagde resultate. Huidige hoë pryse vir CLT in Suid-Afrika is 'n afskrikmiddel vir die aanvaarding daarvan as 'n konstruksiemateriaal. Hierdie vooruitsig word verder vererger deur die voorspelde houttekorte in die komende jare. As sodanig is dit noodsaaklik om die ontwikkeling van innoverende, laerkoste CLT-vervaardigingsprosesse te oorweeg, ondersteun deur grondstofoptimalisering. Hierdie navorsing het die integrasie van vervaardiging van hout en CLT ondersoek met die doel om die eenheidskoste van CLT as 'n produk te verminder.

Verhoogde bastoelaag (IW) en verhoogde bastoelaag gekombineer met enige-breedtes (IW+RW) het aansienlik verbeterde volume-herwinnings in alle blokklasse getoon. Deur die maksimum bastoelaag-scenario van (dikte =75%, breedte =50% en lengte =100%), is die gesimuleerde volume herwinning geïnterpoleer na werklike saagmeul volume herstel, as 'n geweegde gemiddelde van gesimuleerde opbrengste. Maksimum gemiddelde geweegde volume-herwinning vir 'n tipiese klein-hout-saagmeul was 63.5% vir die verhoogde bastoelaag gekombineer met enige-breedtes scenario (IW+RW), nou gevolg deur verhoogde bastoelaag (IW) scenario op 61.5% onderskeidelik. Hierdie volume-herwinningsresultate dui op baie hoë verbeterings in vergelyking met die huidige volume-herwinnings wat in tipiese saagmeulens in Suid-Afrika behaal word.

Tien CLT panele is vervaardig en getoets tot faling en meganiese buigeienskappe is bepaal. Prominente falingsmodus van die buigtoetse was die bros spanningsfaling, wat voortgespruit het uit die CLT onderste longitudinale laag. Die gemete kwaseienskappe van die middelste gedeelte van die CLT panele het geen beduidende korrelasie met MOE gehad nie. Die eksperimentele buigstyfheid van elke CLT-paneel is dan vergelyk met sy voorspelde meganiese eienskappe gebaseer op die skuif-analogie-metode vir ladings loodreg op vlak gebaseer op die globale styfheidsmetings. Die vergelykings tussen voorspelde en eksperimentele resultate vir die drie bas-toelaaggroepe, ten spyte van klein steekproefgrootte, toon noue ooreenkomste. Resultate van die hoë bas-kategorie het getoon dat die insluiting van 'n aansienlike baspersentasie in CLT binne die kruislamellas nie die buigstyfheid van die CLT-paneel beïnvloed het nie. 'n Vergelyking tussen die eksperimentele buigmoment van die monster CLT panele en voorspelde buigmoment van vervaardigde CLT paneel is uitgevoer. Die berekende eksperimentele buigmoment (FbS) resultate het tussen 7.2 en 12.5 N. mm gewissel terwyl die voorspelde buigmoment vir S5 CLT (FbSeff) 2.2 N.mm was. Van die vyf panele wat erge bas gehad het, het twee 'n FbS-waarde laer as 10 N.mm/m gehad. Van die vyf matige en lae-bas panele het geen waardes laer as 10 N.mm/m gehad nie. Dit wil dus voorkom asof die hoë bastoelaag tot laer FbS-waardes kon gelei het. As dit teenwoordig is, blyk die omvang van hierdie effek nog redelik klein te wees. Dit is waarskynlik dat die laer bindingsarea as gevolg van gapings veroorsaak deur bas verantwoordelik was vir die waargenome laer FbS waardes. Oor die algemeen toon die resultate 'n goeie aanduiding van die potensiële gebruik van basplanke in CLT-produksie. CLT-vervaardiging met verhoogde bastoelae-planke het gelei tot 'n hoë benutting van laerwaarde-hout, dus verhoogde waarde-onttrekking per enkele stomp. Soos getuig deur die suksesvolle ontwerp, toetsing en validering van die eksperimentele werk wat in hierdie navorsing onderneem is, blyk dit dat waardekettingintegrasie baie potensiaal inhou om die koste van CLT in Suid-Afrika te verminder.

Sleutelwoorde: CLT; Simulasie Optimalisering; Waardetoevoeging; Willekeurige wydtes (RW); Verhoogde Wane; Integrasie; Waarde ketting; Buigmoment; Buig styfheid; Skuif analogie model

This thesis is dedicated to my family, I thank God for their companionship.

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It is always good to have an end to a journey towards, but in the end, it is the journey towards that matters.

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List of abbreviations

MOE - Modulus of elasticity
MOR- Modulus of rupture
SANS – South African National Standard
CLT – Cross Laminated Timber
SED -Small end diameter
EN - European Standards for Structural Use
AS -American Standards
SSP-Standard sawing pattern
RW-Random Widths
IW- Increased wane allowance
SA – South African

Chapter 1: Introduction

1.1 Background

Increased acceptance and adoption of cross-laminated timber (CLT), offers exiting opportunities from a sawmill industry and green building perspective. Within the South African context, the cost of CLT is relatively high. In a recent study, Van der Westhuyzen (2020) investigated the economic feasibility of a multi-storey mass timber structure within a South African context. An eight-storey mass timber structure and a similar reinforced concrete structure were designed. The study concluded that 10% more investment was required for the development of the mass timber structure. The current high CLT prices in South Africa makes it less competitive compared to other structural building materials. Whilst the advantages of CLT are well documented, for it to attain scale as a product and impact the South African construction industry, there is a need for innovative efforts to position it as an affordable building solution.

Measurable impact and sustainability of manufacturing CLT in South Africa is dependent on lumber cost and availability (Crafford and Wessels, 2020). The log resources in the country remain constant, if not dwindling in the foreseeable future. Crafford (2013),, Crafford and Wessels (2016),, Dugmore (2018) and Crafford and Wessels (2020), cited a predicted timber supply deficit, with improved demand in the timber market, and a sustainable building drive as potential timber supply shortage drivers within the South African context. Growth in mass timber initiatives would therefore present an inevitable demand strain. Consequently, log processing optimization and innovative applications that drive increased product availability and value could gain fresh significance (Rappold et al., 2007; Missanjo and Magodi, 2015).

Lumber yield is affected by several factors including log shape, log size, saw kerf size and sawing patterns (Baltrusaitis and Pranckeviciene, 2005). The dimensions of products to be sawn from a log also influence yield (Görgün and Ünsal, 2017). Accordingly sawing patterns that offer a limited set of products geometrically, will reduce opportunities for optimum recovery from the log. An economically viable shift from current sawing patterns and sawn products, can potentially offer cost reduction opportunities in the sawmill value chain.

1.1.1 Sawing optimization

When sawing patterns are optimized, there are increased opportunities to extract value from the logs. A sawing pattern in Figure 1 (a) depicts a conservative sawing approach whilst in Figure 1 (b) an aggressive approach is presented, with sawing specifications altered; aiming to maximize lumber output per log, even though the sawn lumber may include wane or random width boards.

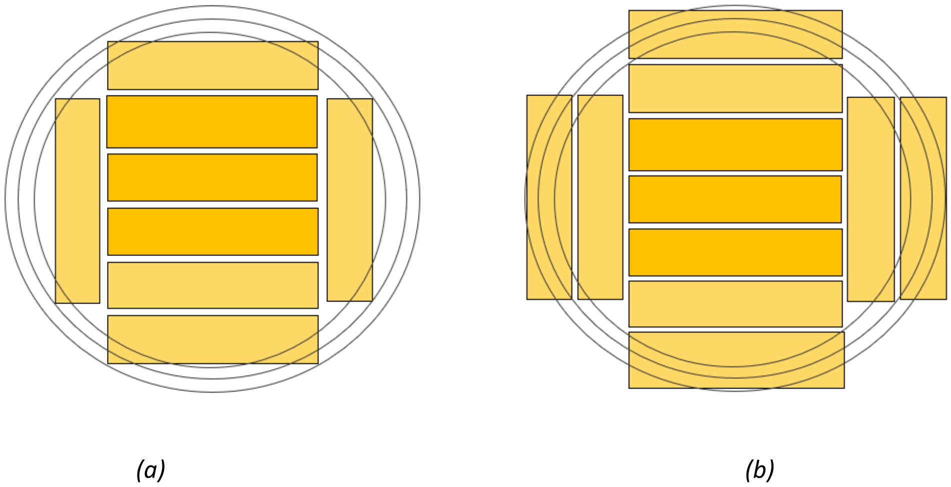

Figure 1: Classic cutting pattern of a log, depicting the concept of recovery. (a) Shows a standard sawing pattern and (b) sawing pattern that accommodates more wane.

Sawmills try to produce as much high-grade lumber as possible, influenced by good demand and market prices. The lumber volume recovery of a sawmill typically ranges from 40-55% (Lindner et al., 2015). The remaining fraction comprises of sawdust, chips, and bark as detailed in Figure 2.

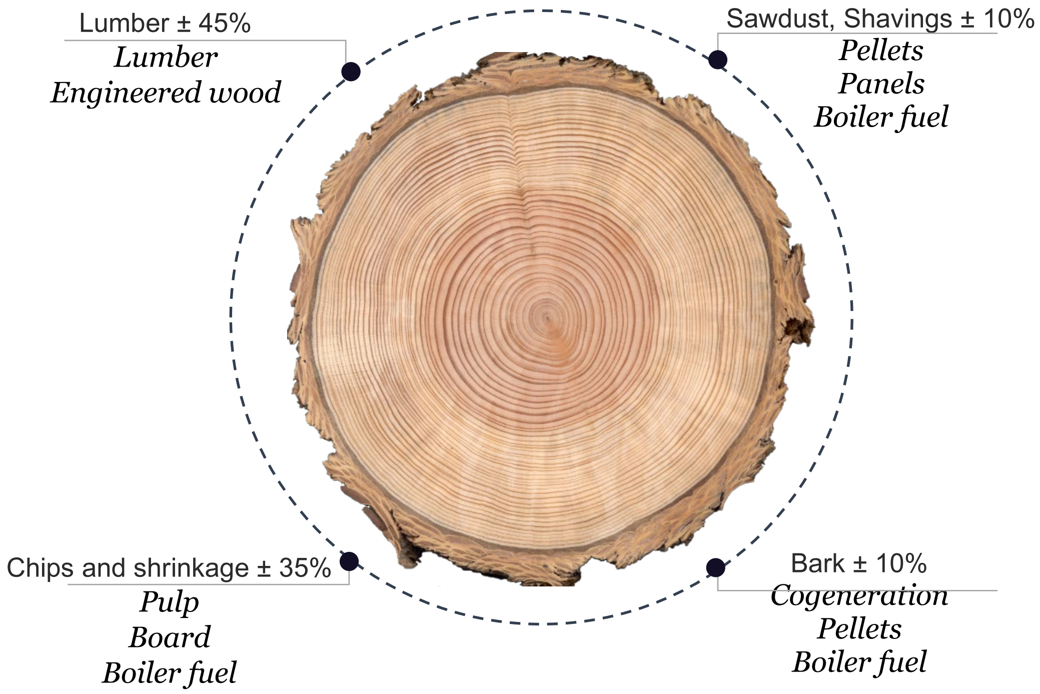

Figure 2: Wood products from conventional log conversion.

1.2 Problem statement

The drive for the effective use of raw materials in the wood products field is well documented (Dugmore, 2018; Eggers et al., 2010; Crafford and Wessels, 2020). Within the South African perspective, improving efficiency per unit log utilization remains a challenge as well as an opportunity.

The thesis of improving volume recovery against a backdrop of high log costs and the need to maximise their use, calls for holistic and integrated approaches. As such, efforts to minimise raw material losses should be complimented with downstream opportunities that can readily assimilate the salvaged lumber volume (Brege et al., 2010).

Improved economic gains could be achieved by picking the right raw material and processing it more intelligently based on knowledge of the logs (Steele et al. 1993; Todoroki 2001). Sawmills can potentially also improve volume recovery by employing sawing strategies that allow increased wane allowance or use of random width material. Although some of the lumber resulting from this operation would be classified as of low grade, its successful application in the development of value-added products would provide case for progressive and inclusive sawing strategies. New revenue opportunities for the low-grade lumber could initiate a rethink of the current sawmill production decisions towards solutions that maximise lumber output per given log with a holistic inclusiveness, targeting products such as CLT.

Potential exists for the use of low value lumber in the development of value-added products such as CLT. It is an additive engineered wood product whose basic components are alternating layers of face glued boards called lamellas. These are currently being made mostly from high value structural lumber. CLT manufacturing costs consist of lumber, glue and labour, with lumber contributing most of the total cost (Brandt et al., 2019). Reducing these high lumber costs from a CLT perspective could unlock various opportunities ranging from better sawmill profits, reduced CLT selling prices and improved CLT adoption.

This research proposes an integrated sawmill and CLT processing facility, to improve raw material conversion efficiency in a sawmill and reduce lumber input cost from a CLT perspective. Two strategies are proposed viz. increased allowance of wane edges in boards, and the use of random width lumber.

During CLT manufacturing, wane edged boards otherwise classified as low value lumber could be positioned in the middle lamellae, whilst the high value lumber is designated to the top and bottom lamellae, respectively. This opportunity will yield economic benefit for both the sawmill and the CLT processing plant mainly through value addition to the sawmill residues, and creation of a fresh revenue stream. Sawmill simulation is widely accepted as a powerful tool for quantifying such opportunities.

The basic problem this research needs to address is therefore that an economic improvement opportunity exists of integrating the sawmill and CLT value chains which need to be quantified. This information is required for potential future investment decisions in such a production facility.

1.3 Research objectives

This research aims to explore the feasibility of manufacturing value added CLT from SA pine lumber utilising increased wane allowance and random width boards in the sawing strategy. Its two main objectives are disseminated in Table 1.

Table 1: Research objectives.

Main Objectives	Secondary Objectives	Deliverables
• To evaluate the potential increase in volume recovery when a SA Pine sawmill includes random widths and increased wane allowance in its sawing strategy.	• To quantify increases in volume recovery achievable when including wane edges and random widths scenarios by using sawmill simulation software.	• Simulate normal sawmill production and compare with inclusion of different with wane and random widths scenarios
	• To experimentally compare simulation software outputs against a real-world sawmill output in order to validate simulation results.	• Simulate the same sawmill process, and compare the results with real world sawmill recovery
• To investigate the effect of increased wane allowance on SA Pine CLT strength and stiffness performance.		• Manufacture CLT panels with different wane allowances. • Quantify wane surface area of each panel manufactured. • Conduct bending tests of CLT according to SANS 8892

Chapter 2: Literature review

2.1 Concept of volume and value recovery

Sustained productivity growth has a significant influence on the long-term competitiveness of a sawmill as a business (Sasatani, 2009). Lumber volume recovery is widely used to determine sawmill productivity. It measures the efficiency with which lumber is recovered from a log during the log breakdown the process. For the purposes of this thesis volume recovery is expressed as percentage of lumber generated from total input log volume.

Equation 1: Volume recovery calculation.

$$Volume\ Recovery = \frac{Product\ volume}{Log\ Volume} x100$$

A higher volume recovery therefore denotes a favourable log breakdown conversion. This directly influences sawmill profits, with higher volume recovery rates usually translating to favourable profits (Ray et al., 2007).

Volume recovery however does not quantify other salient sawn lumber value determinants such as lumber size or grade (Wade et al., 1992; Olufemi et al., 2012). A better alternative for ascertaining mill efficiency would be measuring the actual yield of the processed logs against an established mill standard yield by log and lumber grade (Ray et al., 2007) . Value recovery and net value recovery, although not always a popular efficiency measure, is a more comprehensive metric (Wessels, 2018). It quantifies the value created per volume of logs processed (Fonseca, 2005) with net value recovery measuring the margin per log volume input.

2.2 Optimizing volume and value recovery

Lumber grade yields ascertain the value of the recovered lumber as per market demand. Sawmills therefore need to find ways to optimize the volume recovery and the value of the output lumber to maximize their profits (Görgün and Ünsal, 2017).

The demand for certain grades of lumber compels sawmills to tailor their production towards meeting that demand (Johansson, 2007). Coupled with drastic changes in the global forestry industry, many sawmilling and wood products companies have since started to shift their production strategies (Dougherty et al., 2009; Hughes et al., 2014). There is a departure from generic lumber production towards more value- added product offerings and efficient management of residues (Hughes et al., 2014; Ahmad et al., 2017).

2.3 Simulation

Simulation is one of the prominent tools used across various industries to promote efficiencies and optimization of processes (Ching, 2013). Within the sawmilling sector, various simulation packages are used (Todoroki and Ronnqvist, 1999; Nordmark, 2005; Fredriksson et al., 2015; Stängle et al., 2015; Barbour et al., 2003). The use of technology in sawmills assists in making sound judgments on the placement of edge and trim saws to produce maximum board volume (Schmoldt et al., 1998).

The existence of sawing simulation models can be harnessed to test different scenarios in a virtual world, thereby supporting production as well as creating information for management, decision-making, and process control (Pinto et. al, 2005; Campbell, 2013). Sawmill managers can effectively analyse their current operations and investigate the impact of different sawing strategies.

Wood exhibits variation, with each individual log being unique. These variations influence the lumber yield obtained from each log. For a simulation environment to correctly mimic the real-world logs, it is essential to this real-world variation is induced. Measurable log properties that affect volume recovery as discussed by Maness and Donald (1994) and Edward Thomas and Bennett (2017) and Baltrusaitis and Pranckeviciene (2005), are illustrated in Figure 3. The cutting of a log is an irreversible process (Görgün and Ünsal, 2017), and simulation provides an opportunity to model virtual logs that accurately predict a sawmill's possible log inventory.

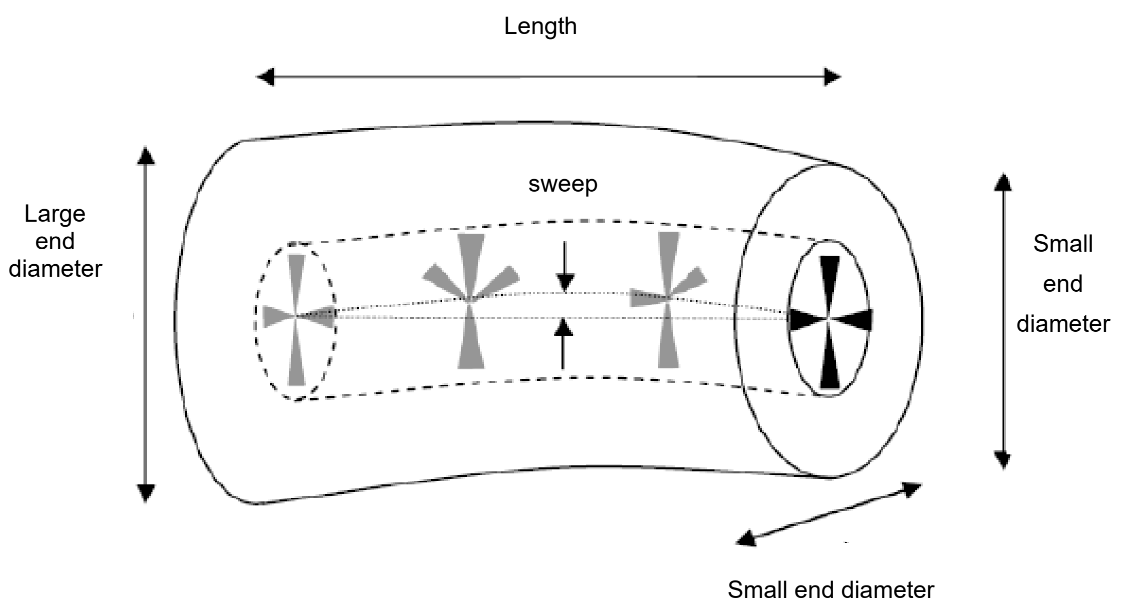

Figure 3: Log dimensional, shape and quality characteristics (Wessels, 2018).

2.4 Wane in wood processing

During the sawing process, logs are cut into boards. Most flitches and boards exhibit bark or jagged edges in outer areas. Wane refers to the portion of bark or rough unfinished wood that is left on the board during sawing (Sohrabi, 2013). It is classified as a defect, comprised of either bark or missing wood on an edge of a board (Görgün and Ünsal, 2017).

Excess wane is removed by edger's and trimmers. Within accepted wane limits, waney edged boards can still be processed into lumber, whilst those exhibiting excess wane are usually processed into other wood products (Carpenter et al., 1989). Wane on a piece of lumber can be expressed as a percentage or fraction of the sum of measured wane pockets along the full board length, width, or thickness (Sohrabi, 2013).

The presence of wane does not usually reduce lumber strength significantly. Wane is also present on outer boards where properties such as wood density is usually at a maximum and microfibril angle at a minimum (Wessels at el., 2015). Wane is usually restricted in structural timber. The South African National Standard (SANS) stipulates the maximum allowable wane in structural and industrial grade timber (SANS 1783-3, 2010).

2.5 Random widths

Random widths are usually sawn in small scale high value lumber sawmills, where there are no grades to specify standard widths. In a larger sawmill, sideboards and flitches can be trimmed and edged in unorthodox widths, resulting in a versatile product mix (together with standard widths of centre boards) that optimizes log volume recovery. Random widths boards can also contain wane, thereby maximizing log utilization.

2.6 CLT as a product

CLT is made up of orthogonally stacked odd layers of wood, each being called a lamella. An adhesive is applied to the faces of the lamellas. Afterwards the assembled product is pressed at high pressure (Mohammad et al., 2012). CLT can reduce the influence of wood defects, which would normally disqualify lower value lumber for structural applications (Dugmore et al., 2019).

CLT possesses numerous advantages as a construction material, including structural and environmental performance as well as speed and efficiency at which the CLT buildings can be erected (Song and Hong, 2018). Its thickness allows it to be used as a stand-alone structural element with high mechanical properties (Klippel et al., 2016). This opens up new markets for timber engineering, enabling its use in bigger structures (Marko et al., 2016; Klippel et al., 2016). As such, CLT is now a good competitor and alternative to reinforced concrete (Schickhofer and Bauer, 2016).

2.7 CLT mechanical properties

Since CLT is mainly used as large-sized stand-alone structural element for load-bearing purposes, it is manufactured to meet structural standards. To effectively apply structural timber, it is essential to have good knowledge of the CLT mechanical properties (Romer, 2013; Brandner et al., 2008; Song and Hong, 2018).

Models are often used to predict the strength and stiffness performance of CLT panels made up of different species and grades (Song and Hong, 2018). To analyse bending or shear resisting properties, a comparison can me bade from calculated specimen mechanical properties against ones from a model, to determine the accuracy of a model. The Shear analogy model, Timoshenko and Gamma method are some of the models that have been used in literature to predict strength properties (Song and Hong, 2018; Rose et al., 2018; Niederwestberg et al., 2018; Montgomery et al., 2014).

2.8 Use of low value lumber in CLT

There has been research towards innovative CLT manufacturing within the South African context looking at ways to utilize lower value lumber such as fast-growing pulp log *Eucalyptus grandis* (Dugmore, 2018; Dugmore et al., 2019; Proller et al., 2019; Wessels at al., 2020; Alade et al. 2021). This research builds on that albeit from an optimization of current sawmill sawing processes perspective. In literature two avenues of low value lumber are explored viz. firstly, leveraging on current low value by products from normal lumber sawing and sawing processes and secondly utilization of species whose lumber have not been used in structural applications, such as hardwoods.

2.8.1 Innovative use of current sawn timber

Laminated timber products also provide an opportunity to control the location of higher-grade timber in the engineered section to maximise structural benefit (Rose et al., 2018). Other products such as glulam already allow the production of structurally sound products from lower value lumber, with stiffer lumber on the outside whilst weaker lumber is positioned in the neutral axis. European structural calculations in CLT discount the contributions of the crosswise layers, as can be attested by the Gamma method.

Rose et al.,(2018), investigated exploitation of construction waste timber as CLT base material. The MOE and MOR of the CLT was highly affected by poor finger jointing of the short boards and base material defects in the used timber. The removal of areas with concentrated defects on the reclaimed lumber was suggested. Experimental results suggested that the use of high-quality secondary timber in crosswise lamellas of CLT is plausible. CLT with lower strength properties could also be used in instances where structural needs are lower, for instance non-load bearing CLT components.

Lawrence (2018), investigated the use of lumber from small diameter logs obtained from forest thinning operations. This would then be used in core layers of CLT panels. The technical viability of 5 layered panels was compared with characteristic engineering properties of standard CLT grade benchmarks. The panel’s shear properties were within the set standards of the PRG 320-2012. However, most of the samples did not meet the cyclic delamination and block shear minimum. Challenges in processing thinned trees were highlighted. As such, failures were reportedly attributed to problems that transpired within the manufacturing process. A similar study suggested that pinewood obtained from plantation thinning could be used as a CLT base material (Baño et al., 2016).

2.8.2 Low value lumber from alternative species

To broaden the range of wood available for CLT manufacturing, other species such as black spruce have been used to manufacture CLT, whose properties were comparable to those of the CLT manufactured from other commonly used lumber (Song and Hong, 2018).

Owing to less availability of high value lumber, Marko et al. (2016) investigated the use of poplar in CLT manufacturing. Due to lower resultant MOE's of the CLT panels it was suggested that poplar can still be used as a mix-in species, in conjunction with other softwood materials or premium grade poplar could be used (Marko et al., 2016).

Thomas and Buehlmann (2017) investigated the lumber yield from low grade hardwood timber with the view of utilizing it in CLT. Yellow poplar was also used due to its abundance, cheap price as well as good mechanical properties compared to softwoods. The research, however, focused on volume recovery studies, whilst canvassing for further research encompassing CLT manufacturing and testing.

An assortment of bamboo and wood was used for CLT manufacturing in a study by (Barreto et al., 2019). The observed strength properties of the cross-laminated timber-bamboo observed were greater than those prescribed by the (American National Standards Institutes (ANSI-PRG), 2012). The panels were structurally efficient, with higher strength properties compared to other lower value lumber containing CLT in literature.

2.9 Conclusion

The literature review covered the economic and technical aspects that give insight into the subject. Sawmill simulation, log breakdown processes and CLT as a product and the use of Low value lumber in CLT were unpacked.

Chapter 3: Materials and methods

This chapter consists of three sections. The first (Section 3.1) presented the real-world sawmill simulation trial, disseminating the steps undertaken within the process. The second (Section 3.2) articulates the simulation process, themes and scenarios of sawing using random widths and increased wane allowance strategies. Lastly Section 3.3 concludes the chapter by the outlining the CLT making process and strength testing procedure of the same. The progression and interplay of these sections is outlined in Figure 4.

Take note that in the text, tables and figures the following abbreviations are often used:

- Random widths (RW)
- Increased wane allowance (IW)

3.1 Sawmill trial

This section seeks to investigate the accuracy of the Simsaw 6 suite in predicting a sawmill's yield.

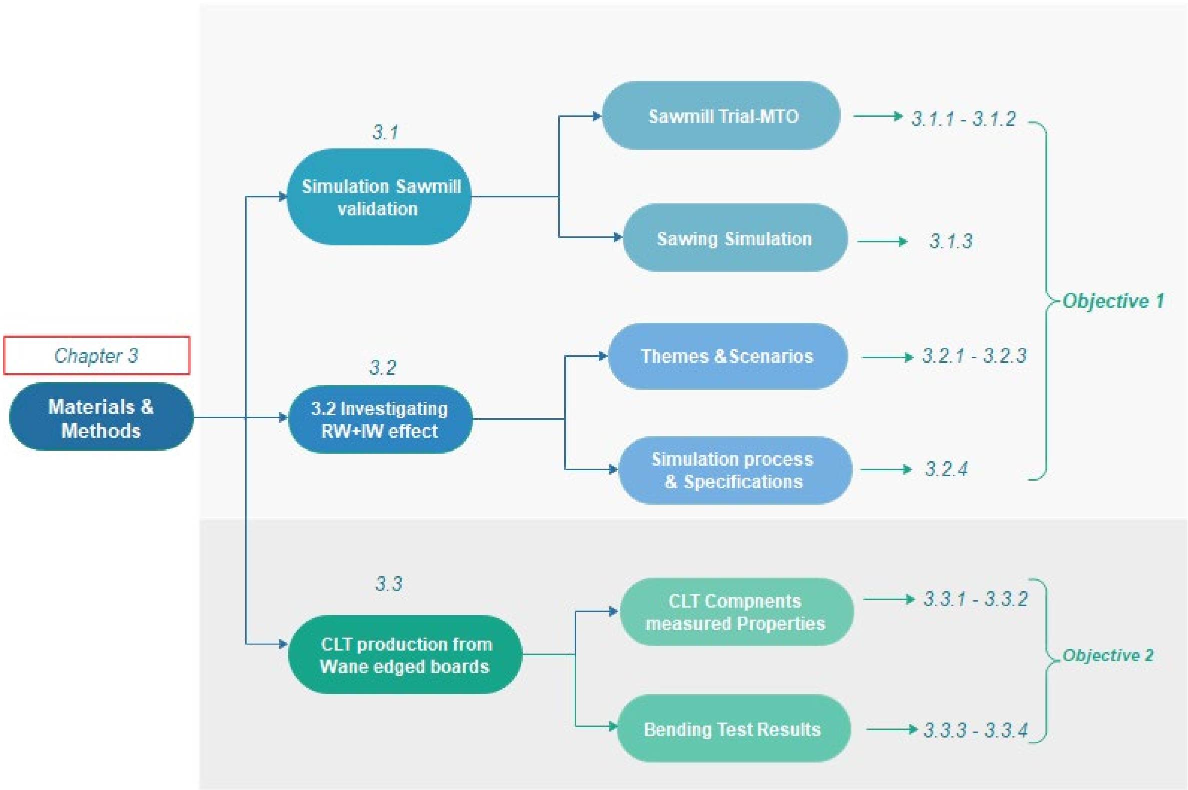

Figure 4: Chapter 3 progression, facilitating experimental investigation of the three research sections.

3.1.1 Study overview

Sawmill recovery studies were performed on pine logs that were supplied by the MTO George sawmill's log yard. Simsaw 6 sawmill optimization software, a sawing simulation tool which predicts the sawn board recovery from logs, given certain inputs was used (Wessels et al., 2001). The study was conducted, as shown, in two stages. During the first stage, the properties of the sample logs were measured. Characteristics essential for log volume recovery calculation or re-generation in Simsaw 6 were measured. The logs were then sawn into boards in a mechanised sawmill, subject to the consideration of permitted defects including wane.

In the second phase, the recorded log specifications and the sawmill's machine properties were replicated in a sawing simulation of the logs. Lastly, a comparison between the results of the two process was conducted. Figure 5 depicts the experiment progression.

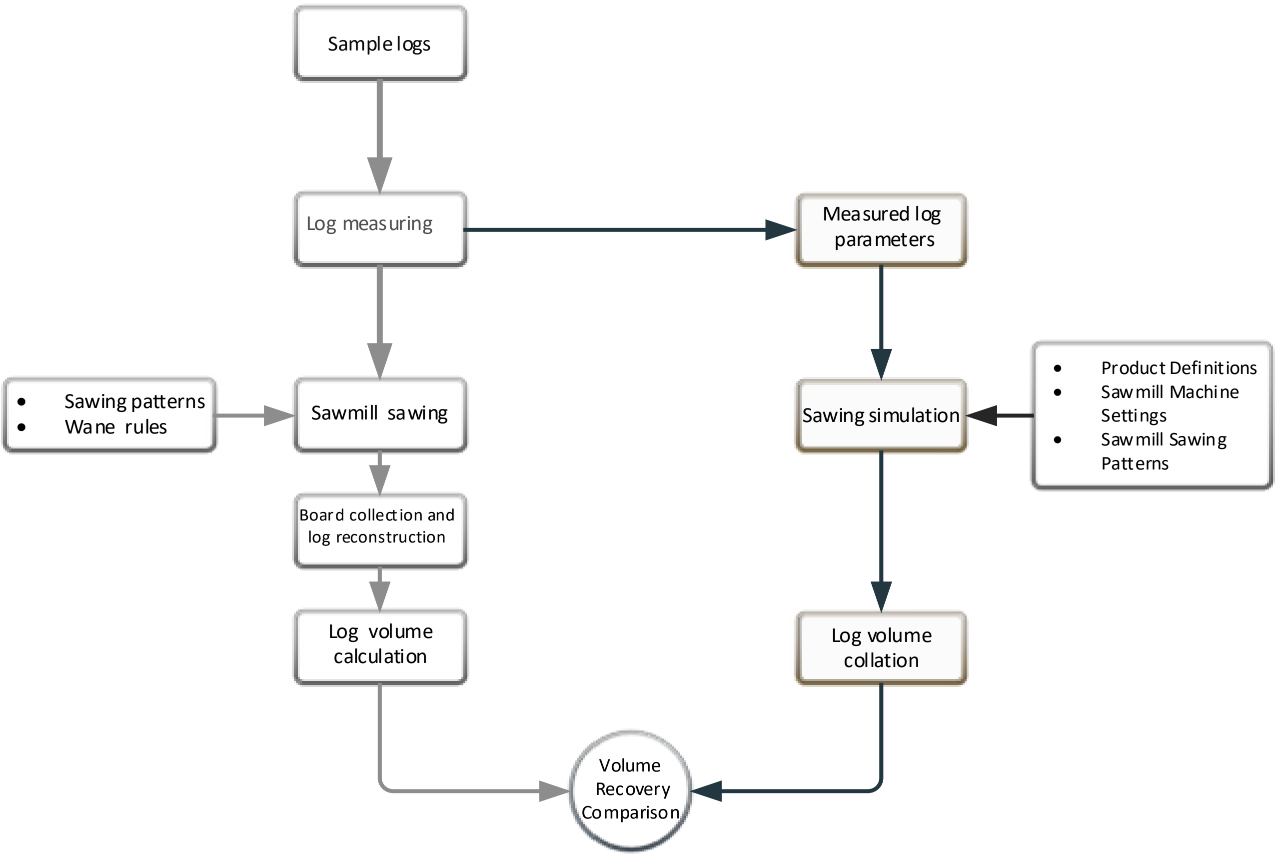

Figure 5: Process flow diagram followed in this study. The left-hand side presents the activities conducted in the real-world sawmill process. The right-hand side presents the simulation activities.

3.1.2 Sawmill processing

3.1.2.1 Materials

A sample of two classes of pine logs was selected from the sawmill log yard. Logs arrived at the log yard already bucked in lengths of between 2,4 m and 4,8 m. The two classes consisted of a small log class of diameters ranging between 18 to 23,9 cm and large log class of diameters ranging between 24 to 27,9 cm.

Ten logs from each of the two classes were set aside from the log yard for measuring. The sample logs had not been debarked yet, providing a good platform to measure the external log properties. A builder's line, a tape measure and coloured spraying paint of five distinct bright colours facilitated the measuring process.

The small logs class was sawn on the first day, in line with the mill's production scheduleand the large log class was then sawn on the following day. Since logs constituting both classes were taken from the same log yard during a wet period of the year, there was no expected significant difference between the log properties due to external conditions.

3.1.2.2 Measured properties

3.1.2.2.1 Log preparation and measurement

The logs in each class were separated into two batches of five. To facilitate the identification and tracking of each log during sawing and collection of the boards, a different colour was applied to either ends of the five logs. The colours used were red, white, purple, blue and yellow. Since the length of the sample logs differed with some measuring less than 4,2 m whilst others up to 4,9m, where possible, a shorter log and a longer log of the same class were painted with the same colour. This difference in length would make it possible to identify the log from which sawn boards were generated, in the case of ambiguity.

The use of smaller batches ensured easy handling of logs before they were sawn and transparent identification of the corresponding boards after being pulled off from the green chain. This improved the accuracy of the results by reducing handling errors in the collation and re- building of logs from the sawn boards.

3.1.2.2.2 Diameter measurement

The South African log volumes are usually calculated using uneven under bark- small end diameters. For this study, the small end under-bark diameter for the logs were measured using a tape measure. It was measured as the average of two diameter measurements taken at right angles to each other across the face of the log. Maximum small end diameter and the diameter perpendicular to it were recorded as shown in Figure 6. The same process was repeated for all logs.

These measurements facilitated the calculation of the log volumes and derived properties such as ovality. The log ovality which is the average deviation of the cross-section area, was calculated as the maximum measured log diameter divided by the perpendicular diameter to the maximum diameter.

Equation 2: Ovality calculation

$$Ovality = \frac{Diameter\ A\ (mm)}{Diameter\ perpendicular\ to\ A\ (mm)}$$

(a) *(b)*

Figure 6: Diameter measurement process. (a) Maximum diameter measurement (b) Measurement of diameter perpendicular to the maximum diameter.

3.1.2.2.3 Log orientation

The rotational position for each log that would allow it to lie in a horns-up position was identified and marked with a visible vertical line. The ‘true north’ of the log was demarcated for the purpose of giving the sawyer guidance when feeding the log into the headrig. The logs were therefore sawn in the same axis from which the log properties were measured. Figure 7 shows the distinct vertical marks that would allow the log to be sawn as centred as possible, with the side of the log with most sweep facing upwards. The reason for this was to be able to simulate sawing of the logs in the same position as in the real sawmill.

(a) *(b)*

Figure 7: Marking of the vertical position of the log orientation in relation to the sweep of the log.

3.1.2.2.4 Sweep measurement

The amount of sweep in a log is measured as the deflection from a straight centre line drawn from one end to another. Figure 8 depicts vector $\vec{c}$, a straight line touching both ends of the log at the centre – which is the definition of sweep, also in the Simsaw simulation software. For the purposes of this research sweep measurement was taken at the point of highest deviation, as shown by vector$\vec{a}$, in Figure 8, but which should approximate $\vec{c}$ accurately.

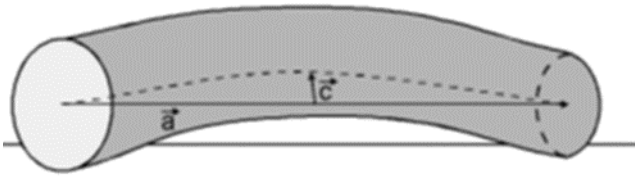

Figure 8: Log sweep illustration, showing the end-to-end line.

A builder's line was secured tight at both ends of the log at the point of highest deviation. The maximum perpendicular deviation of the line to the log surface was then measured using a tape measure. The procedure depicted in Figure 8, was undertaken for both log classes. Sweep measurements procedure undertaken for this study is depicted in Figure 9. The measured results are presented in Table 2 and Table 3.

(a) *(b)*

Figure 9: Sweep measurement during the experiment. (a) A builder's line secured at both ends of the log and sweep measurements being taken at the point of highest deviation from the log surface. (b) A close-up of the sweep measurement showing the sweep of a log.

3.1.2.2.5 Sawing preparation

After all the measurements, colouring and vertical positioning orientation were completed, the logs were kept in the two separate batches, ready to be fed into the mill as shown in Figure 10. External defects that could compromise the grade of sawn lumber from a log were examined. These included big knots, rot, insect damage, and mechanical defects.

Figure 10: Logs separated into two batches after the necessary measurement have been taken, readying for sawing at the headrig

3.1.2.2.6 Measured log properties

The measured log properties for the two log classes are presented in Table 2 and Table ***3***. Log length, diameter, and sweep are presented for each individual log. The external log properties are also detailed.

Table 2: Summary of measured small log properties

Log Number	Length (m)	Under Bark Small End Diameter		Ovality	Sweep (mm/m)	Log Volume (m^3)	External Log Properties
		Diameter A (mm)	Diameter B (mm)				
1	4,90	185	180	1,03	10,20	0,173	Damaged on the side
2	4,88	185	182	1,02	6,15	0,173	None
3	4,31	205	183	1,12	4,87	0,147	Big Knots can be seen
4	4,92	190	183	1,04	6,10	0,173	None
5	4,95	280	220	1,27	2,42	0,283	Knots
6	4,90	195	184	1,06	11,24	0,173	None
7	4,89	198	194	1,02	2,25	0,173	None
8	3,68	220	200	1,10	5,44	0,147	Big Knots on the sides
9	3,71	215	210	1,02	9,16	0,147	None
10	3,72	192	189	1,02	5,11	0,122	None

As seen in Table 2, some logs in the smaller log class exhibited external damage. In Table 3 it can be identified that none of the logs within the larger log class had significant external damage that could influence the log's volume recovery. Log scaling was done according to the standard method used in South Africa for softwood sawlogs (SA Forestry Handbook, 2000).

Table 3: Summary of large log class measured properties

		Under Bark Small End Diameter					
Log No	**Length (m)**	**Diameter A (mm)**	**Diameter (mm)**	**Ovality**	**Sweep (mm/m)**	**Log Volume (m^3)**	**External Log Properties**
1	4,90	261	244	1,07	9,36	0,283	None
2	4,92	255	244	1,05	4,17	0,283	None
3	4,24	282	220	1,28	10,7	0,242	None
4	4,92	236	227	1,04	8,54	0,243	None
5	4,92	256	240	1,07	3,13	0,283	None
6	4,87	245	235	1,04	5,21	0,283	None
7	4,29	245	245	1,00	13,1	0,242	None
8	3,70	235	230	1,02	6,94	0,174	None
9	3,70	241	222	1,09	8,89	0,174	None
10	4,92	242	238	1,02	6,46	0,283	None

3.1.2.4 Log breakdown methods applied at the MTO Sawmill

The MTO Timbers sawmill uses the cant sawing method which is the most popular sawing method when sawing pines in South Africa (Wessels, 2018; Lindner et al., 2015).

1. **<u>Sawing Specifications</u>**

A double band saw machine was used during primary breakdown and a NKV multi-ripping machine was used for secondary log breakdown. For the first cut, the logs were fed into the bandsaw, in a rotated horns-down (crook down) position and centred in-between the two saws at the headrig. The optimizing edger was used to recover lumber from sideboards. The boards were not crosscut in order to keep the coloured board ends. The sawing machine and resaw settings applied during sawing are detailed in Table 4.

Table 4: Machine Settings

	Number of Kerf sizes	**Inside Blades (mm)**	**Outside blades (mm)**
Primary Breakdown	1	5	0
Secondary Breakdown	1	5. 4	0

Edging/ X-Cut/Resaw	**Number of Edging blades**	**Primary Kerf (mm)**	**Secondary Kerf (mm)**
	2	3. 2	3. 2

2. Machine Specifications

Distinct sawing patterns were used for sawing each of the two log classes owing to differences in their small end diameters (SED). Within the log class, however, the same sawing pattern was used for all the individual logs. The adopted sawing patterns are listed in Table 5. The centre boards were cut to 38 x 114 mm (wet dimension: 40 x 120 mm) and 38 x 152 mm (wet dimension: 40 x160 mm) respectively.

Table 5: Sawing patterns used for the two log classes in the sawmill

Log classification	Log class (SED) (cm)	Primary Sawing pattern (mm)	Secondary Sawing pattern (mm)
Small Log class	(19-21 cm)	25/114/25	2*25 2*38 3*25
Large Log class	(27-29 cm)	25/152/25	3*25 3*38 3*25

3.1.2.5 Sawmill processing

3.1 2.5.1 Log reconstruction for board volume calculation

During secondary log breakdown the boards were only edged; no cross- cut operations were performed. Cross cutting would remove the coloured end of the boards, complicating their assignment to their respective logs.

Centre boards and un-edged side boards were pulled off from the green chain and separated according to their colour. Boards from the same log were collated, as if to reconstruct the log. This facilitated accurate board to log allocation and measurement of the sawn lumber volume. Boards from reconstructed individual logs are shown in Figure 11.

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Figure 11: Boards sorted into individual logs; vertical markings showing orientation of log feed at headrig can be seen on some of the boards

3.1.2.5.2 Manual sawn board mensuration and quality rules

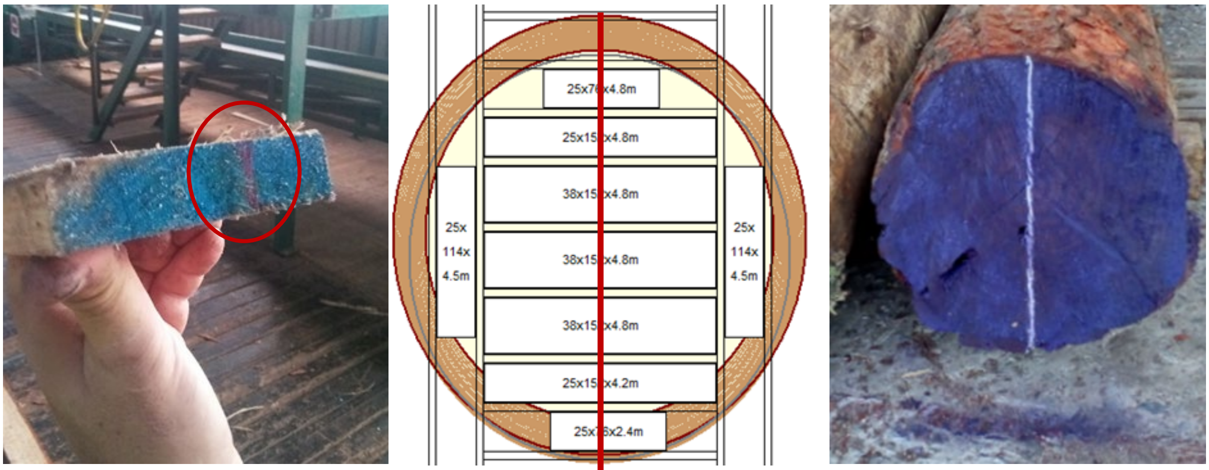
The MTO sawmill's lumber quality standards were adopted for the sawmill study. Wane, knot size, rot and external damage were of primary focus. An expert from the sawmill manually graded each board for wane and other defects in accordance with the sawmill's lumber grading rules which were within the South African National Standards (SANS) lumber grading rules. The wane specifications and possible board dimensions were established and manually demarcated as illustrated in Figure 12. Features outside of the defined limits were regarded as waste off-cuts.

(a) (b)

Figure 12: Determining and demarcating the length of the board after considering the applicable wane rules. (a) Manually determining the cross-cut position. (b) Marking the board length and width.

3.1.2.5.3 Sawing Validation

Validating a simulation study, gives confidence in its use to deduce simulated results into real world solutions within the sawmilling processes (Fredriksson, Berglund, et al., 2015). It seeks to substantiate simulated processes within a satisfactory range of accuracy (Sargent, 2008). At the headrig, logs were sawn oriented in a horns down position, the direction of the highest sweep. The orientation of the vertical line demarcation on the sawn centre boards in Figure 13 (a), confirms the correct log infeed orientation at the headrig. Volume recovery was calculated for each log as the total board volume produced from each log (dry dimensions) as a percentage of the log volume.



(a) (b) (c)

Figure 13: Vertical orientation of the demarcation on sawn boards. (a) A vertical mark on a sawn board (b) The expected layout and mark orientation when the log is fed in correct position. (c) The vertical mark orientation layout on a log.

3.1.3 Sawing simulation

The sawmill benchmarking study sought to establish the deviation between sawmill sawn lumber volume recovery and simulated lumber recovery of the same sawmill, using the same logs, machine properties and sawing patterns. The Simsaw 6 inputs on the original interface for all the populated data inputs in this section are detailed in Appendix A.

The process followed in simulating the MTO George sawing process is discussed in this section. Simsaw 6 was used for the investigation. The software is used in some South African sawmills to optimize sawing decisions. In this study, the software's user inputs including log definitions, product definitions, machine settings and sawing patterns were entered to mimic the real-world sawn sawmill operation.

3.1.3.1 Log generation

The measured log characteristics detailed previously in Table 2 and Table 3 were used to recreate the logs in Simsaw 6. The real logs option could not be used with the inputs available. This meant that outputs might be slightly less accurate than when the actual log shape was used as input. Logs were generated in Simsaw 6 as per specifications of the measured logs.

3.1.3.2 Board dimensions

The board grading rules used during the sawing process were adopted for the simulation study. As previously stated, wet mill board grading was based on wane and other external features such as pitch pockets or rot. It is notable that the external properties or log damage cannot be simulated in the Simsaw 6 suite.

Within Simsaw 6, the dimensions of the boards were defined by their wet and dry thickness and widths. Wane specifications were also defined and populated. Wane specifications allowed at the MTO George sawmill illustrated in Table 6 were populated, comprising of 30% wane for both thickness and width, and 50% lengthwise respectively.

Table 6: Board definitions dimensions and the defined wane specifications for the sawmill trial

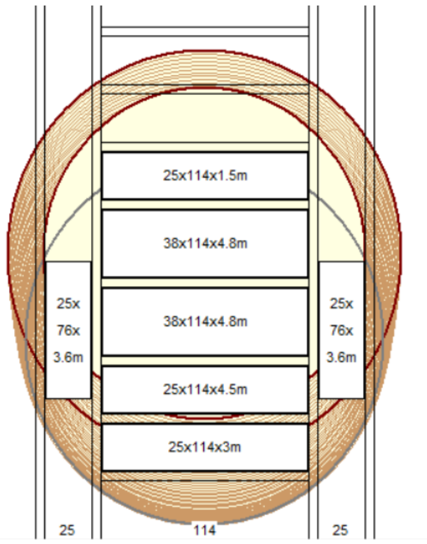
Thickness (mm)		Widths (mm)		Wane allowed (%)		
Dry	Wet	Dry	Wet	Thickness	Width	Length
25	28	76	81	30	30	50
30	40	102	108	30	30	50
		114	120	30	30	50
		152	160	30	30	50

3.1.3.3 Machine settings

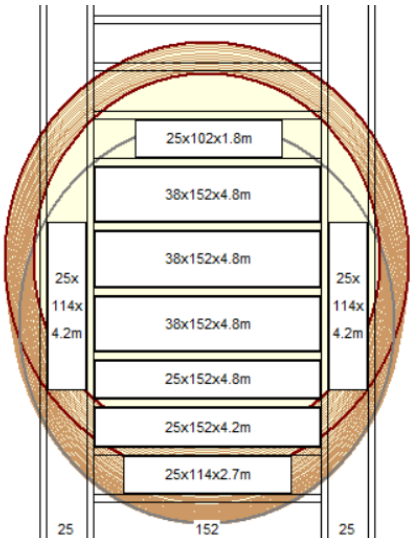
The machine settings used during sawmill sawing, were applied on a cant sawing pattern for primary and secondary breakdown as well as for edging and resaw processes. These were discussed previously in Table 4.

3.1.3.4 Sawing patterns

Simsaw 6 allows user customization of desired sawing patterns for a modelled sawmill. During the simulation process, the cant sawing method was used, as shown in Figure 14. Small logs followed a 25/114/15 sawing pattern for the primary breakdown and 2*25 2*38 3*25 for the secondary breakdown. The large logs followed a 25/152/25 for the primary breakdown pattern and a secondary breakdown pattern of 3*25 3*38 3*25. The software edged and trimmed side boards based on the machine settings presented previously in Table 4.



(a)



(b)

Figure 14: The sawing patterns used for the two log classes, (a) small logs and (b) for the large logs

3.2 Sawmill simulation

This section describes the simulation and evaluation of the effect of random widths and increased wane allowance sawing strategies on the volume recovery of sawn lumber. Four themes were investigated namely, the standard sawing pattern (SSP) which is the standard way logs are processed in most sawmills, allowing random widths (RW), allowing increased wane allowance (IW), and lastly the combination of random widths with increased wane allowance (RW+ IW).

The real logs option of the Simsaw 6 simulation package was used to simulate the sawing process. A cant sawing production line was used across all the four scenarios.

<u>Definitions</u>

Theme – A distinct sawmill sawing option characterizing a specific set of product definitions (SSP, RW, IW, RW+IW).

Scenario – Each theme is made up of one or more scenarios, structured and simulated to investigate the impact of different combinations of product specifications on volume recovery.

Wane Combinations – Each scenario is made up of varying wane combinations on the three axes of a board, for instance, Thickness: 30%, Width: 20 and Length: 50% wane on each edge.

3.2.1 Grading Rules for Wane

The SANS national grading rules detail the limitations in permitted lumber characteristics. They detail the worst-case scenario for each defect and characteristic of dimension lumber allowed in each grade. The rules therefore describe the poorest pieces permitted in a grade, limiting the defects on a board.

Discussion with sawmillers alerted us to the fact that actual rules applied differ from that specified in SANS 1783-2 (2012). The wane rules that some sawmills use, including the HM Weza sawmill, are shown in Table 7. This specifies the amount of wane that can be allowed on a sawn board. Table 8 shows the SANS wane rules.

Table 7: Wane rules used in some South African sawmills

Timber size and Grade	Allowable Wane %		
	Thickness	Width	Length
Structural>38 mm	10%	10%	100%
Industrial> 25 mm	30%	10%	100%

Table 8: Maximum allowed wane by SANS for structural and utility grade timber categories (SANS1783-3)

Timber size and Grade	Allowable Wane %		
	Thickness	Width	Length
Structural > 38 mm	50	30	100
Industrial>25 mm	30	25/20	100

3.2.2 Defining the sawing scenarios in a Theme

In this subsection, the scenarios in each of the three themes are defined, outlining the sawing strategy employed.

3.2.2.1 Standard sawing pattern (SSP)

This theme is made up of standard sawing dimensions being used across most South African sawmills. The product dimensions and wane rules allowed in this category for the purpose of this study are detailed Table 9.

Table 9: Standard board definitions dimensions and the defined wane specifications constituting the SSP

Thickness (mm)		Widths (mm)		Wane (%)		
Dry	Wet	Dry	Wet	Thickness	Width	Length
25	28	76	81	30	30	100
38	40	102	108	30	30	100
		114	120	30	30	100
		152	160	30	30	100

3.2.2.1.1 Sawing strategy employed

Log sawing cutting patterns chosen for this sawmill were driven by maximum recovery. Resaws were present and sawing patterns contained 50mm thickness products which are not often in a real-world sawmill. Therefore, results should be interpreted with that in mind.

3.2.2.2 Increased wane allowance (IW)

Increased wane allowance (IW) involves the deliberate inclusion of additional wane on the edges of a sawn board, during the secondary log breakdown process. Figure 15 details the effect of increased wane allowance on the dimensions of the sawn boards. Increasing the wane would improve the width of flitches during edging, similarly their length. As labelled on the side view of a board, A represents a board being cut using wane specifications that are currently allowed within South African Sawmills. B depicts the possible width generated using increased wane allowance (IW), whilst C shows possible improvement in the trimmed board length.

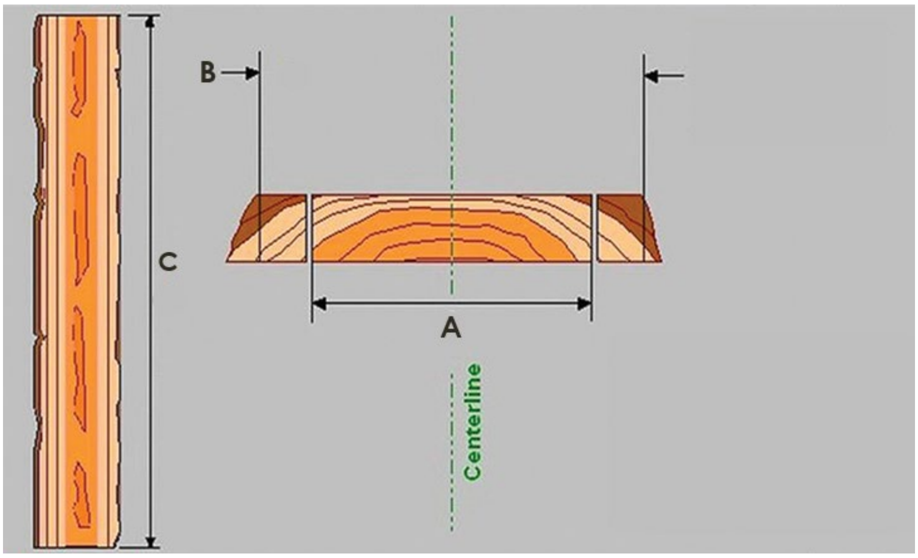


Figure 15: Increased wane sawing during the secondary log breakdown process

3.2.2.3 Random widths (RW)

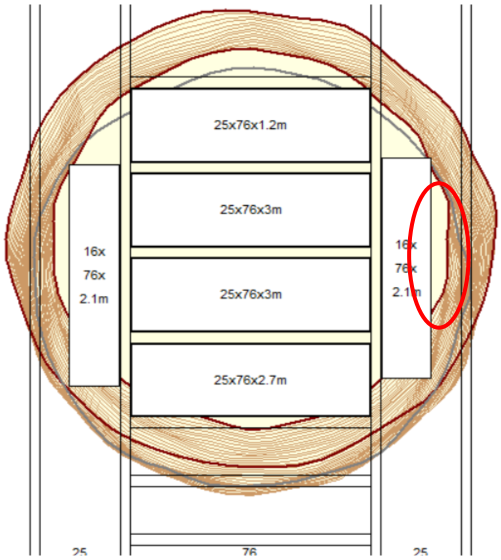
The functionality of sawing by incorporating random widths (RW) is illustrated in Table 10. Using current SANS standard lumber width dimensions, the width of the trimmed or edged boards is restricted to 76,114,152 or 228 mm. This results in other dimensions being cut to fit into these four widths, thereby limiting the lumber yield.

On the other hand, random widths (RW) improve the volume recovered at the edging/resawing process by offering high flexibility in widths that flitches can be trimmed to. Table 10 unpacks the difference between these two processes. Widths can be varied from 50 to 230 mm at 10 mm increments. This enables the sawmill to optimize on volume recovered from the flitches.

Table 10: Illustration of the random widths (RW) sawing

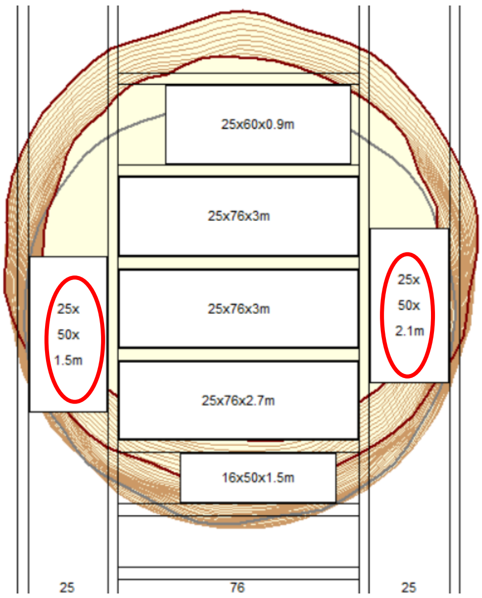
Current Widths Rules
•76 •114 •152 •228

- Boards edged to standard dimensions according to SANS.
- In use across most South African sawmills
- Limited widths to which flitches can be edged/ trimmed. opportunity for improved volume recovery



Random Widths
•50 •60 •76 •80 •. •. •230

- Flexible widths from which flicthes are edged or trimmed
- Wider flitches can be cut as compared to the standard sawing rules
- Improved volume recovery due to wider boards being edged



3.2.3 Simulated combinations for each theme

3.2.3.1 Standard sawing pattern (SSP)

One base case SSP simulation scenario was conducted, mimicking the real-world log properties, sawmill machine settings, product definitions and sawing patterns. The product definitions previously presented in Table 9 were simulated.

3.2.3.2 Random widths (RW)

Only one base case RW simulation scenario was run, within the provision of real-world log properties, sawmill machine settings, product definitions and sawing patterns. The varying widths to which the flitches could be cut to, during the secondary breakdown process are detailed in Table 11. It is essential to note that RW sawing also comprises of SSP widths as well. The RW widths are in italics for illustrative purposes, complementing other widths that constitute the SSP assortment. Allowed wane was akin to the SSP wane currently being used in most South African sawmills.

Table 11: Random widths allowed the sawmill to cut boards from 50mm to 228mm wide in 10 mm increments, including the standard board sizes.

Thickness (mm)		Widths (mm)	
Dry	Wet	Dry	Wet
25	28	*50*	*53*
30	40	*60*	*63*
		76	81
		80	*84*
		90	*96*
		100	*106*
		.	*.*
		.	*.*
		200	*224*
		228	240

3.2.3.3 Increased wane allowance (IW)

To understand the effect of increased wane allowance on volume recovery of a sawmill, a total of 125 simulation scenarios were created. Each constituted of structured, varying wane combinations from a thickness, length, and width perspective. This enabled the investigation of the effect of different combinations of increased wane. All the scenarios were simulated using the SSP as the base case, with wane increments being varied per each scenario. The wane increment percentage points considered on each axis of the board, are presented in Table 12.

Table 12: Base wane specifications to be permutated to make wane combination for the 125 simulated scenarios

Wane allowance variations		
Thickness (%)	Width (%)	Length (%)
75	50	100
60	40	80
45	30	60
30	20	40
15	10	20

The maximum allowed dimensions of the simulated boards in a simulation scenario are detailed in Table 12. Maximum allowable percentage wane on each of the three axes of a board were: thickness-80%, width -50% and length -100%. The wane variations across the three dimensions were permutated against each, resulting in 125 different wane combination scenarios, which are presented in Table 13.

3.2.3.4 Combined random widths and increased wane allowance (RW+IW)

The structuring of the simulation scenarios was the same as discussed for (SSP). Log definitions, machine settings and sawing patterns remained unchanged. The RW base case was used (Table 11), hence the product definitions included the comprehensive widths that are part of the RW theme. Wane increments (Table 13) for each of the 125 scenarios were done using the permutated wane combinations.

3.2.4 Applied sawmill simulation settings in Simsaw 6

Real logs, according to the Simsaw 6's definition of real logs, were simulated and were characteristic of a typical small-log sawmill. Seven log classes were created, based on log sizes. The range of log diameters was selected to cover the diameter classes making up the largest volumes in typical South African softwood sawmills. The 190 simulated logs were allocated to each class to mimic log distribution within a real-world sawmill. The log definitions, product definitions, machine settings and sawing patterns used for the simulating scenarios previously discussed, are detailed in Appendix B. Log size class variation in sawmills can vary depending on supply constraints but results from this study can be weighted if required for application to a sawmill with a different log intake distribution.

3.2.4.1 Simulation verification and validation

Verification was done throughout the simulation modelling. All the aspects of the simulated study accurately represented a sawmill by matching the log parameters, sawmill machines and sawing patterns. Errors were constantly checked at each stage of simulation. Simulation validation was done in a different sawmill simulation study in sections 3.1 and 4.1. This process included mimicking the real-world sawmill environment in the Simsaw 6 simulated model.

Table 13: Simulated wane increment scenarios

No	T	W	L	**No**	T	W	L	**No**	T	W	L	**No**	T	W	L	**No**	T	W	L
1	75	50	100	**26**	60	50	100	**51**	45	50	100	**76**	35	50	100	**101**	15	50	100
2	75	50	80	**27**	60	50	80	**52**	45	50	80	**77**	35	50	80	**102**	15	50	80
3	75	50	60	**28**	60	50	**60**	**53**	45	50	60	**78**	35	50	60	**103**	15	50	60
4	75	50	40	**29**	60	50	40	**54**	45	50	40	**79**	35	50	40	**104**	15	50	40
5	75	50	20	**30**	60	50	20	**55**	45	50	20	**80**	35	50	20	**105**	15	50	20
6	75	40	100	**31**	60	40	100	**56**	45	40	100	**81**	35	40	100	**106**	15	40	100
7	75	40	80	**32**	60	40	80	**57**	45	40	80	**82**	35	40	80	**107**	15	40	80
8	75	40	60	**33**	60	40	60	**58**	45	40	60	**83**	35	40	60	**108**	15	40	60
9	75	40	40	**34**	60	40	40	**59**	45	40	40	**84**	35	40	40	**109**	15	40	40
10	75	40	20	**35**	60	40	20	**60**	45	40	20	**85**	35	40	20	**110**	15	40	20
11	75	30	100	**36**	60	30	100	**61**	45	30	100	**86**	35	30	100	**111**	15	30	100
12	75	30	80	**37**	60	30	80	**62**	45	30	80	**87**	35	30	80	**112**	15	30	80
13	75	30	60	**38**	60	30	60	**63**	45	30	60	**88**	35	30	60	**113**	15	30	60
14	75	30	40	**39**	60	30	40	**64**	45	30	40	**89**	35	30	40	**114**	15	30	40
15	75	30	20	**40**	60	30	20	**65**	45	30	20	**90**	35	30	20	**115**	15	30	20
16	75	20	100	**41**	60	20	100	**66**	45	20	100	**91**	35	20	100	**116**	15	20	100
17	75	20	80	**42**	60	20	80	**67**	45	20	80	**92**	35	20	80	**117**	15	20	80
18	75	20	60	**43**	60	20	60	**68**	45	20	60	**93**	35	20	60	**118**	15	20	60
19	75	20	40	**44**	60	20	40	**69**	45	20	40	**94**	35	20	40	**119**	15	20	40
20	75	20	20	**45**	60	20	20	**70**	45	20	20	**95**	35	20	20	**120**	15	20	20
21	75	10	100	**46**	60	10	100	**71**	45	10	100	**96**	35	10	100	**121**	15	10	100
22	75	10	80	**47**	60	10	80	**72**	45	10	80	**97**	35	10	80	**122**	15	10	80
23	75	10	60	**48**	60	10	60	**73**	45	10	60	**98**	35	10	60	**123**	15	10	60
24	75	10	40	**49**	60	10	40	**74**	45	10	40	**99**	35	10	40	**124**	15	10	40
25	75	10	20	**50**	60	10	20	**75**	45	10	20	**100**	35	10	20	**125**	15	10	20

3.3 CLT Manufacturing

This section describes the bending test of three layered CLT panels. Bending tests were performed on ten CLT panels made from three different groups of wane surface area, the importance of which was to determine the effect of wane surface area on the bending performance.

Bending failure mode in the major strength direction was investigated. Deflection from an Instron machine was used to determine the modulus of elasticity (MOE) of the CLT panels. All ten manufactured CLT boards were further tested to destruction to ascertain MOR values.

3.3.1 Materials

3.3.1.1 Logs

The pine logs used for the experiment were whole logs of either 4.2m or 4.8m length and was processed at the MTO George sawmill.

3.3.1.2 Lumber

The logs provided were sawn into 25 mm thick flitches using the live sawing method. Wider flitches contained less wane (as a percentage of board area) whilst the narrow ones exhibited higher wane as depicted in Figure 16. Flitches were kiln dried at the sawmill. The flitches were then collected and used in the making of CLT boards.

3.3.1.3 Adhesive

Single-component polyurethane “PURBOND HB S309” adhesive was adopted for the CLT manufacturing in this study. It is permissible for use in structural load bearing applications (Purbond, 2013).

3. 3. 2 Methods

3.3.2.2 Board edging

3.3.2.2.1 Clear boards formation

The wider flitches containing small wane amounts, as shown in Figure 16 (a), were edged in the workshop to produce 25*114mm boards without wane on. Most of these boards constituted centre boards of the logs from which they were cut hence the wane was minimal. A total of 70 boards were sawn with their lengths being either 4,2m or 4,8m. These boards constituted the outer lamellas of the CLT samples.

3.3.2.2.2 Wane edged boards

Flitches from the outer surfaces of boards containing significant wane were not edged initially. It was also impossible to cut long 114 wide boards out of them due to higher taper. These boards depicted in Figure 16 (b) were then prepared for use in the middle lamella of the CLT samples.

(a) (b)

Figure 16: Live sawn flitches from which (a) outer lamella boards and (b) crosswise wane edged boards were cut.

3.3.2.2 Determination of the moisture content

Moisture content measurements were conducted less than 24 hours before CLT manufacturing using an electrical resistance moisture meter, with sufficient depth of the electrodes driven into one face of the board in accordance with (EN 16351,,2015).

The accuracy of the moisture meter was also checked, with the meter able to measure the moisture content of the timber within an accuracy of ± 2 % as per (EN 16351, 2015).

3.3.2.3 Board preparation, cutting to length and planing

3.3.2.3.1 Clear boards

The 114mm wide boards produced during the edging process were crosscut into shorter boards of 2,1 m and were planed down to 24 mm thickness.

3.3.2.3.2 Wane edged boards

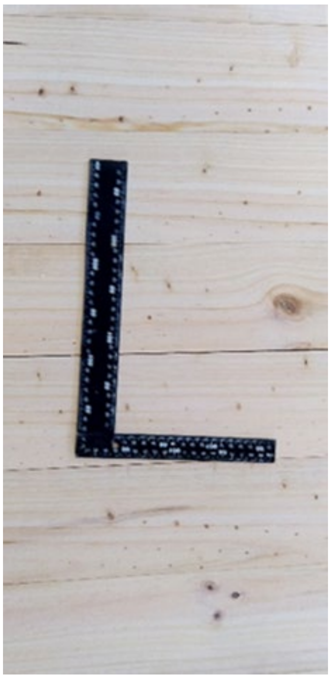
Preparation

The wane edged boards were planed in their sawn length since the thicknesser used for this research could not plane short boards of less than 0,6m. On the day of CLT manufacturing, boards were planed down by 1mm on either side to a final thickness of 22m. This was done to produce a fresh surface which facilitates improved bonding (Yeh et al., 2012).

Cross cutting

Boards were identified and sorted into two groups depending on the severity of wane surface area, namely severe and moderate.

The longer wane edged flitches were then crosscut into 0,342m long boards for cross layers. Using a panel saw, the boards were then edged into 114*342*22 mm boards, whilst aiming to maximizing the wane surface area of the boards. The manufactured wane edged boards are shown in Figure 17.



Severe	*Moderate*	*No wane*

Figure 17: Crosswise lamella wane categories classifications, in preparation for CLT board manufacturing

3.3.2.4 Board arrangement

The top and bottom lamellas of the panel were each made from three 22*114*2100 mm boards. The board position on each lamella in the CLT manufacturing, was predicated by its respective stiffness.

Each board was visibly numbered then bending tests were conducted to determine the stiffness thereof. These were then assigned to a CLT lamella depending on the MOE with the aim of achieving uniform stiffness for each of the ten CLT panels. The mean of the summed stiffness values for each lamella are illustrated in Table 14. Board stiffness for the top and bottom layers were determined from a 4-point bending test conducted according to (SANS 6122, 2017).

3.3.2.5 Wane surface area calculation

Sketch and Calc Software (SketchAndCalc, 2021) was used to calculate the surface area of the wane edges of the transverse boards of the CLT panel. Figure 18 shows the upside face of the middle lamella, with the alternating boards flipped to cater for shear forces during pressing. During wane surface area calculations, the wane surface area of the downside of the lamella was also calculated.

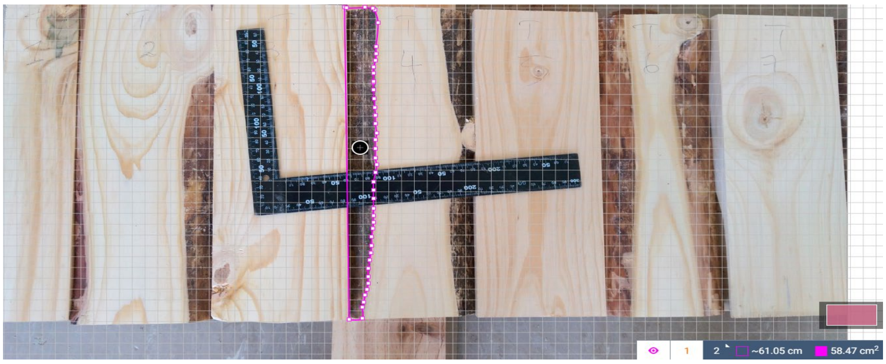


Figure 18: Wane surface area calculation for the CLT middle lamella using Sketch and Calc software

3.3.2.7 Bending test setup and procedure

The bending test was performed according to clause 10 in (EN 16351, 2015). A four-point bending test depicted in Figure 19, was conducted to determine the stiffness of all the boards that would form the outer layers of the three layered CLT boards. An Instron tensile test machine was used consisting of a 5-ton load cell to measure the load. The span distance and crosshead speed were 1950 mm and 20mm/min respectively. The boards measured 2100x 114x22 mm.

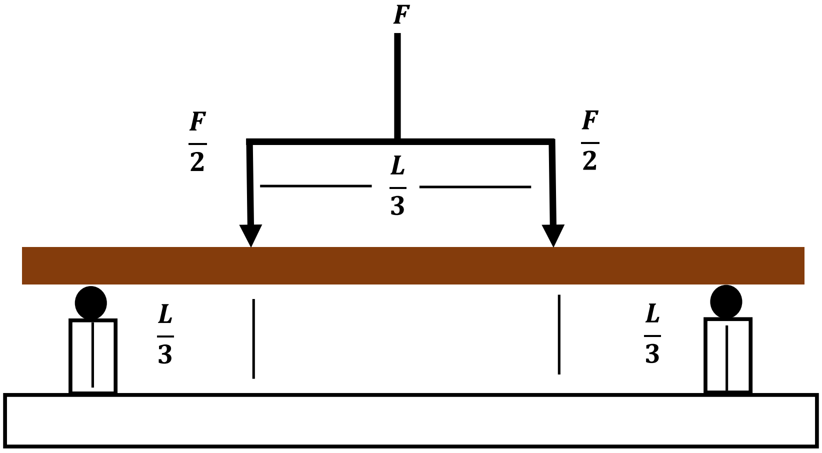


Figure 19: Four-point bending test procedure

Table 14: Calculated board stiffness per each CLT lamella constituent boards (base material)

	Board Stiffness (MPa)								
	Top Layer			Mean	Bottom Layer			Mean	Total Mean
Sample 1	13721	7406	7476	9534	5991	6902	11793	8229	8881
Sample 2	11348	5977	10005	9110	7774	12333	5953	8687	8898
Sample 3	12502	7034	10415	9984	6983	9742	6755	7827	8905
Sample 4	10954	8709	9361	9675	7236	9298	7901	8145	8910
Sample 5	9131	7516	13847	10165	7306	8235	7402	7648	8906
Sample 6	10424	12844	8047	10438	7922	7185	7052	7386	8913
Sample 7	7561	9329	7291	8060	7803	10315	11174	9764	8912
Sample 8	7314	9645	13349	10103	8480	7330	7217	7676	8889
Sample 9	6544	12219	7014	8592	10068	8636	8817	9174	8883
Sample 10	6186	12287	6044	8172	11376	9351	7982	9570	8871

3.3.3 Production of CLT panels

3.3.3.1 Adhesive Specifications

The Purbond HB S309 PUR adhesive used has an assembly time of 30 minutes and a curing time of 75 minutes at 20°C and 65% relative humidity. A pressing force of 0. 6 N/mm^2 to 1. 0 N/mm^2, was recommended. Bonded components are to be stored at 20°C for at least four hours after pressing.

3.3.3.2 CLT Assembly: Bonding surface and application of the adhesive

The Purbond HB S309 adhesive was applied as per manufacturer instructions. Surfaces of the CLT components were freshly planed ensuring that they were free from adhesive repellents or release agents. The climatic conditions of the room was within the glue specfied temperatures.

The glue was decanted and weighed using a scale before being applied uniformly on the two surfaces making up the 3 layered CLT panel. The adhesives were uniformly applied on the face of boards at the required rate of 140-180 g/m^2. Moisture content was measured within 24 hours before the manufacturing of CLT panels and was within specifications.

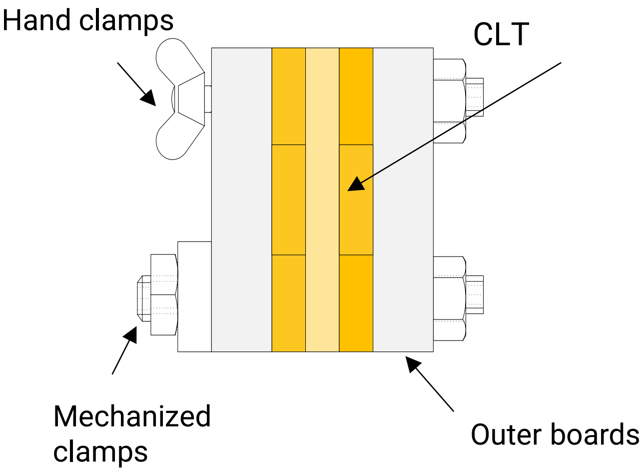
3.3.3.3 CLT Pressing

The boards were face bonded and no edge bonding was done. Three 114mm width clear boards that make the bottom lamella were laid up. Adhesive was applied on their faces and spread uniformly. The wane edged boards were then laid up, alternating the sides with higher wane. This was done to inhibit the wane edged boards to slide over each other during pressing as the wane edged boards reduced edge contact. Adhesive was applied to the face of wane edged boards. Three boards forming the outer lamella of the panel were then laid up on top of the transverse layer.

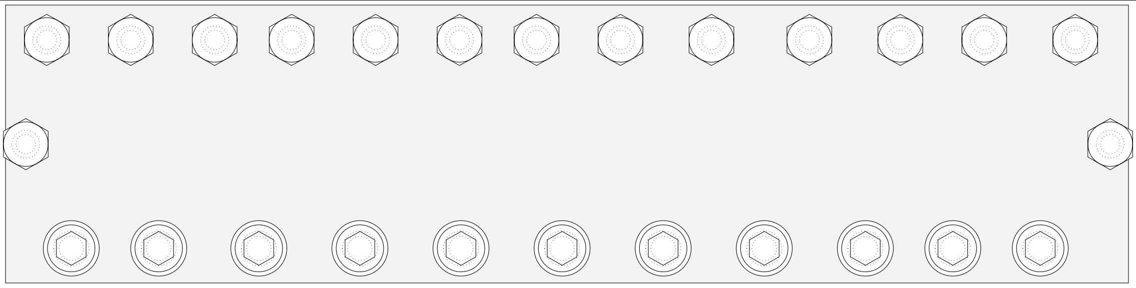
The assembled CLT componets were immidiately lifted and placed on the press and clamped to uniform pressure of roughly 0.75MPa using a torque wrench to control pressure at the bottom section as depicted in Figure 20.

The press time was 90 minutes, slightly higher than the 75 minutes stipulated by the adhesive manufacturer to cater for potential variations in temperature and relative humidity. After curing, the CLT boards were taken off the press and marked with a durable identification. They were then stored at the same temperature and relative humidity (RH) for more than 10 hours in preparation for edging and then finally strength testing.

(a)



(b)



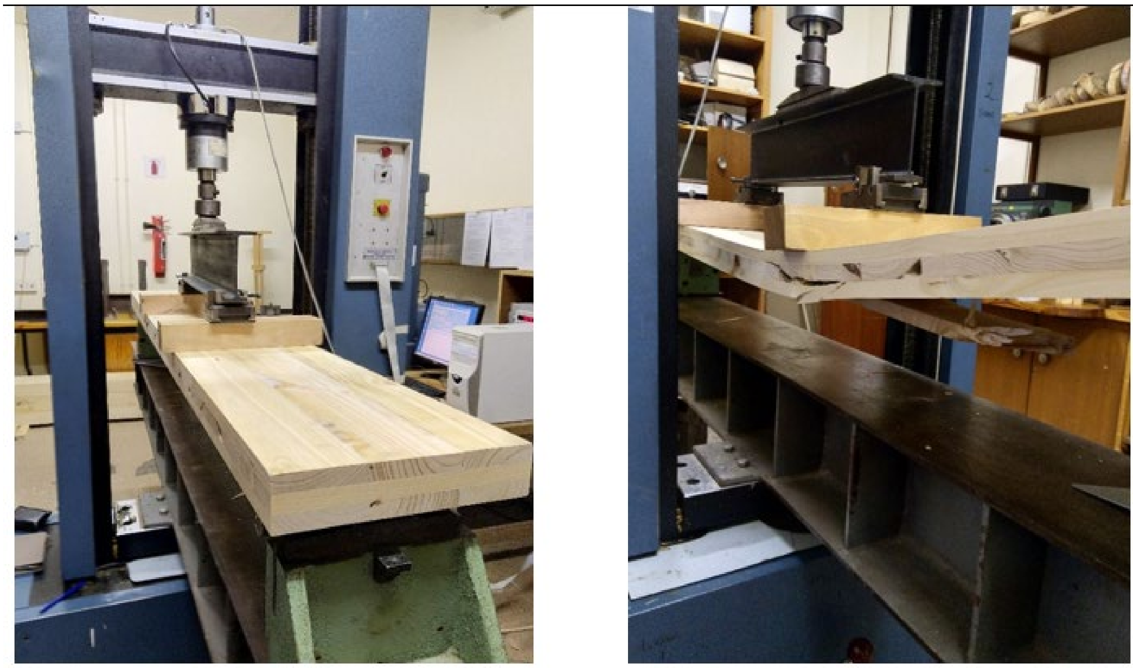
(c)

Figure 20: CLT press system setup

3.3.4 Strength test configuration

The bending tests setup for the Instron machine is shown in Figure 21; (a) shows a full length CLT panel just before application of force, whilst (b) shows the CLT panel after failure.

The test sample properties were similar for all the boards at thickness of 66mm and bending span 1980 mm as recommended by the, PRG-320 and EN 16351 (2015). The deflection of the test specimen was measured automatically by the Instron testing machine. Incorporating the self-weight of the panel, shear and bending moment diagram for the four-point bending test is illustrated in Figure 22. The MOE and MOR were then calculated using the formulas described in the (SANS 6122, 2017).



(a) (b)

Figure 21: Impressions from testing machine setup showing full-length of the CLT board (a) before breaking force application (b) post force application

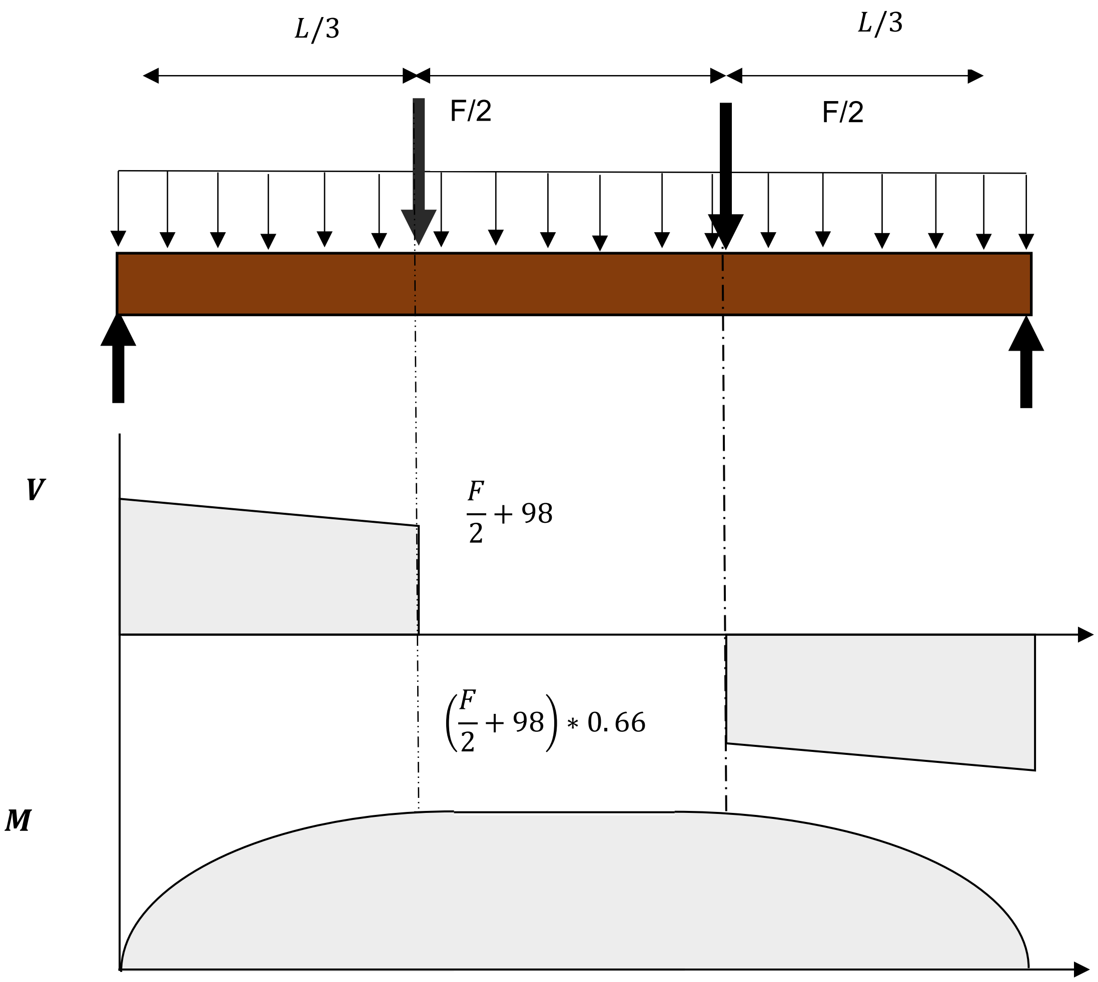


Figure 22: A diagram showing how the shear force V and the bending moment M change over specimen length. Self-weight loading was included.

3.3.5 Knot size measurement

The CLT panels experience tensile forces mainly in the bottom lamella and compressive forces in the top lamella. As such, the size of the knots on boards of the outer lamella of the bottom side was measured to investigate the effect of knot size on the strength of CLT panels.

The knot diameter was measured as the length between two parallel lines tangential to the knot, in the selected axis. Figure 23 depicts the width-wise measurement whilst Figure 24 depicts the lengthwise measurement criteria respectively. The total knot size on a CLT board in an axis was measured as the sum of the individual diameters, across its width or lengthwise within 150mm of the CLT panel's middle section.

Figure 23:Figure: Knot diameter measurement across the width of the panel for CLT board number

Figure 24: Knot diameter measurement lengthwise of CLT panel number 9

3.3.6 Manufactured CLT panels

Side views of the three wane surface area groups considered in this study are depicted in Figure 25.

Wane Properties	
Severe ***Board number: 1 2 3 5***	
Moderate ***Board number: 4 8 9***	
Zero ***Board number: 6 7***	
Severe,, 76mm width ***Board Number: 10***	

Figure 25: Side view of the manufactured CLT panels showing cross-layers of the three different wane groups

Chapter 4: Results and discussions

The progression of Chapter 4 can be viewed in the diagram below (Figure 26).

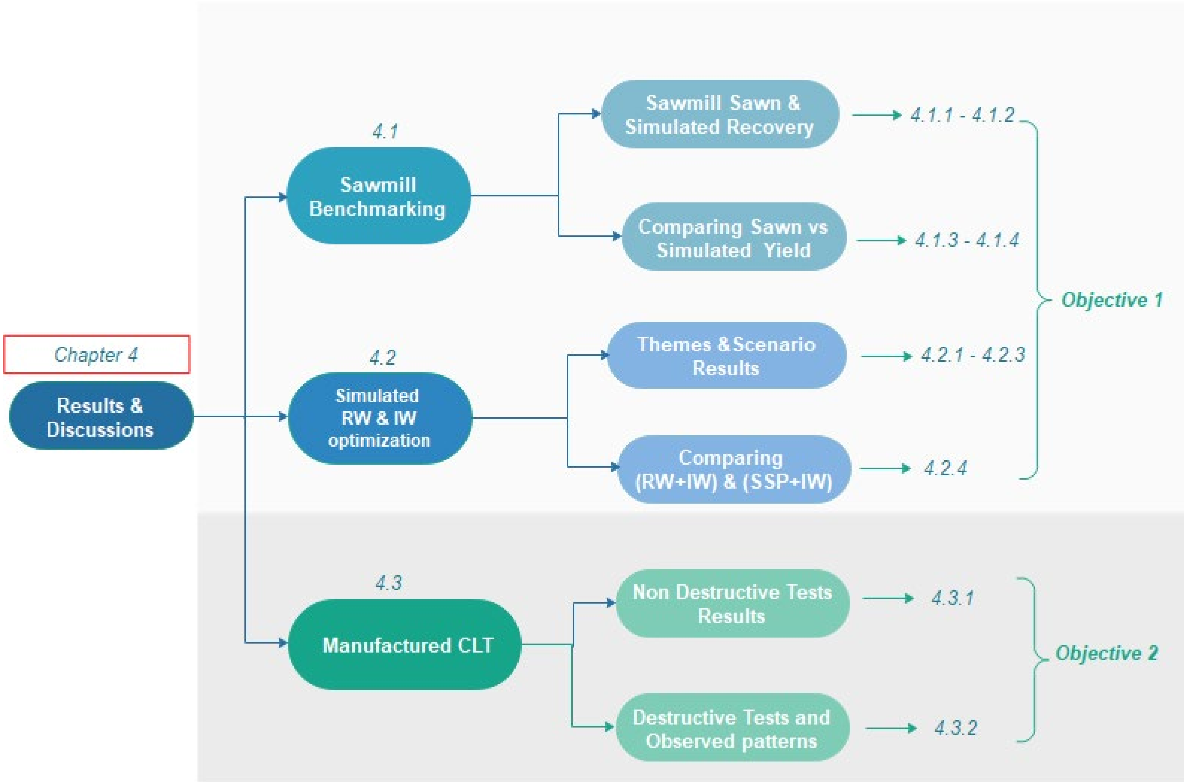


Figure 26: Chapter 4 progression

4.1 Sawmill Benchmarking

This section presents sawn lumber volume recoveries of the small and large logs of the sawmill trial. The simulation results of the replicated real-world sawmill environment are also illustrated. Comparisons drawn between these were outlined, determining the accuracy of the sawmill simulation compared to the real sawmill results.

4.1.1 Comparing sawn and simulated yields per log class

Log yields expressed as percentage volume recoveries within the simulated log class were compared with the real-world sawn log volume recoveries is presented in Table 15.

Given similar log characteristics, sawing patterns, machine specifications and lumber product sizes, the sawn lumber yields varied from simulation yields. This difference between the sawn and simulated log volume recovery gave a good margin to which the software can be used to predict yield in real world sawmills.

The sawn log volume was compared with the simulated volume for each of the ten small logs. Simsaw 6 simulation software overstated simulated volume recoveries by at most 2,4%. The mean deviation was 2,01% as depicted in Table 15.

Table 15: Simulated small log volume recoveries vs sawn lumber recoveries

Sawing Pattern		Log number	Diameter	Volume recovery (%)		Difference (%)
Primary	Secondary			Simulated	Sawn	
25/114/25	2*25 2*38 3*25	1	182,5	46,9	44,9	1,95
		2	183,5	50,8	48,5	2,26
		3	194	47,1	45	2,05
		4	186,5	50,5	48,1	2,37
		5	250	44,8	46	1,2
		6	189,5	47,1	45,1	1,98
		7	196	51,5	50	1,45
		8	210	52,1	49,8	2,27
		9	212,5	51,3	49	2,32
		10	190,5	48,3	46	2,29
Mean (%)			199,5	49,0	47,2	2,01

The mean and 95% confidence intervals for the simulated and sawn small logs volume recovery are shown in Figure 27. The simulated mean of 49,0% and a 47,2% sawn lumber mean are depicted showing that actual results were significantly lower than simulated results.

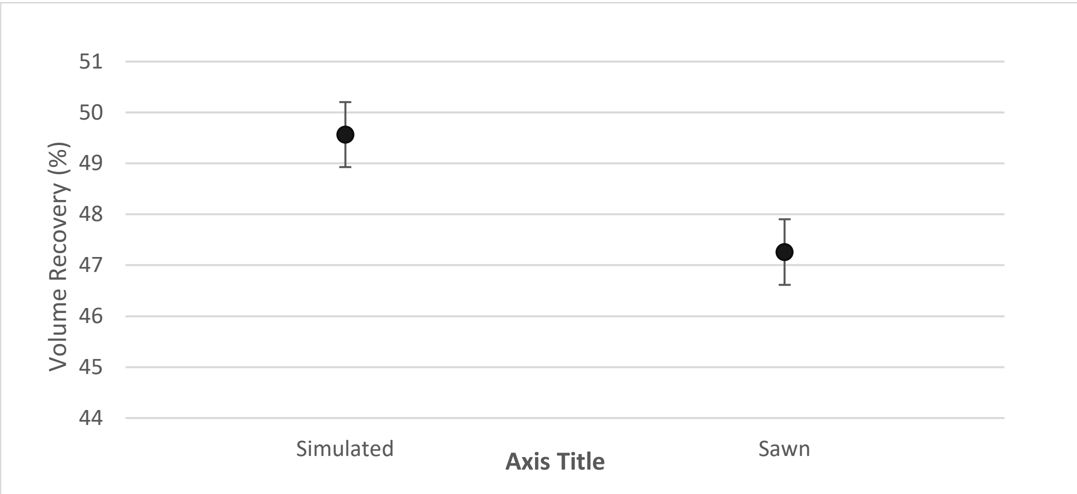


Figure 27: Means and 95% confidence intervals for the simulated and sawn small logs volume recovery

Complimentarily, the dimensions of the boards recovered from the sawn large log class are detailed in Table 16 and are later unpacked in Table 18. Here expected individual large log volume was compared with the simulated volume. Results indicate that volume recovery of Simsaw 6 closely replicates the sawmill processes. It consistently gives overstated simulated volume recoveries of less than 2,49% within range of the actual sawmill volume recovery at most. The mean deviation was 2,01% as depicted in Table 16. This

Table 16: Illustration of simulated against sawn volume recoveries for the large logs sample

Sawing pattern		Log number	Diameter	Volume recovery (%)		Difference (%)
Primary	Secondary			Simulated	Sawn	
25/152/25	2*25 2*38 3*25	1	252,5	54,27	52,03	2,24
		2	249,5	54,56	52,15	2,12
		3	251	53,45	50,86	2,59
		4	231,5	51,24	50,56	0,68
		5	248	54,46	52,35	2,11
		6	240	50,86	48,84	2
		7	245	50,1	48,76	1,34
		8	232,5	56	52,35	3,65
		9	231,5	55	52,92	2,08
		10	240	48,95	46,86	2,49
Mean			242,2	52,9	50,7	2,13

From the compared results, the means and 95% confidence intervals for the simulated and sawn large logs volume recovery were obtained. These are depicted in Figure 28, showing a simulated mean of 52,9% for simulated results and 50,7% for the sawn logs volume of within the large log class.

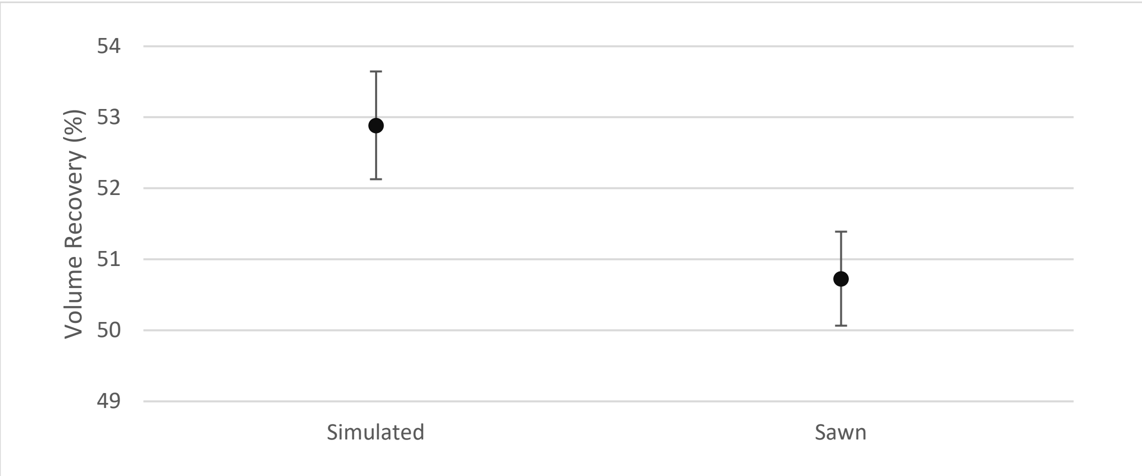


Figure 28: Means and 95% confidence intervals for the simulated and sawn large logs volume recovery

4.1.2 Comparing sawn and simulated board dimensions

The dimensions of the boards recovered from the sawn logs for each log class are detailed in Table 17 and Table 18. Sawn board dimensions for each log were compared to boards generated during simulation to identify the differences per each board. Small logs dimensions are unpacked in Table 17 and large log results in Table 18 respectively. The differing lengths in generated lumber boards are depicted in red, whereas the black colour depicts same boards length per each sawing pattern dimension per individual log.

Table 17: Small logs, sawn vs. simulated board dimensions

Log Number	Sawing pattern dimensions mm	Sawn boards lengths mm	Simulated boards length mm
Log 1	38 by 114	4. 8	4. 8; 4. 8
	25 by 114	4. 8; 4. 8; 3. 6; 3. 3	4. 5; 3. 0; 1. 5
	25 by 102	2. 7	
	25 by 76	1. 5	3. 6; 3. 6
Log 2	38 by 114	4. 8; 4. 8	4. 8; 4. 8
	25 by 114	3. 9	4. 5
	25 by 102	4. 8	4. 8; 1. 8; 1. 5
	25 by 76	3. 9; 2. 7; 1. 5; 1. 8	2. 1; 2. 0
Log 3	38 by 114	4. 2; 4. 2	4. 2; 4. 2
	25 by 114	4. 2; 3. 6	4. 2; 3. 9
	25 by 102		
	25 by 76	3. 6; 2. 1; 1. 8	2. 1; 2. 1; 0. 9
Log 4	38 by 114	4. 8; 4. 8	4. 8; 4. 8
	25 by 114	4. 8	4. 8; 4. 5
	25 by 102	4. 2	
	25 by 76	4. 8; 2. 7; 1. 8	3. 9; 3. 9; 2. 1; 0. 9
Log 5	38 by 114	4. 8; 4. 8	4. 8; 4. 8
	25 by 114	4. 8; 4. 8; 4. 8; 4. 8	4. 8; 4. 8; 4. 8; 4. 8
	25 by 102	4. 8; 4. 2	
	25 by 76	4. 2; 2. 4	4. 8; 4. 8

Log Number	Sawing pattern Dimensions mm	Sawn boards lengths mm	Simulated boards length mm
Log 6	38 by 114	4. 8; 4. 8	4. 8; 4. 8
	25 by 114	4. 2; 2. 4	4. 5; 3. 3
	25 by 102	1. 5	1. 5
	25 by 76	3. 6; 3. 6	3. 6; 3. 6
Log 7	38 by 114	4. 8; 4. 8	4. 8; 4. 8
	25 by 114	4. 8	4. 8; 4. 2
	25 by 102	4. 2	
	25 by 76	3. 9; 2. 4; 1. 5	4. 5; 4. 5; 2. 4
Log 8	38 by 114	3. 6; 3. 6	3. 6; 3. 6
	25 by 114	3. 6; 3. 3; 3. 3	3. 6; 3. 6; 3. 3
	25 by 102		
	25 by 76	3. 6; 3. 2	3. 6; 2. 4
Log 9	38 by 114	3. 6; 3. 6	3. 6; 3. 6
	25 by 114	3. 6; 3. 3	3. 6; 3. 6
	25 by 102	2. 4; 2. 1	3. 6; 3. 3 3. 3
	25 by 76	3. 0	
Log 10	38 by 114	3. 6; 3. 6	3. 6; 3. 6
	25 by 114	3. 6	3. 6; 3. 0
	25 by 102	2. 7; 2. 1	
	25 by 76	2. 1	2,4; 2. 4

Table 18: Large logs, sawn vs simulated board dimensions

Log Number	Sawing pattern Dimensions mm	Sawn boards Lengths mm	Simulated boards Length mm
Log 1	38 by 152	4. 8; 4. 8; 4. 8	4. 8; 4. 8; 4. 8
	25 by 152	4. 8	4. 8
	25 by 114	4. 8; 3. 3	2. 7
	25 by 102		1. 8
	25 by 76	4. 8; 4. 8	
Log 2	38 by 152	4. 8; 4. 8; 4. 8	4. 8; 4. 8; 4. 8
	25 by 152	3. 9	4. 8
	25 by 114	4. 8; 3. 6; 3. 3	4. 8; 4. 2
	25 by 102		
	25 by 76	4. 8; 1. 8	0. 9
Log 4	38 by 152	4. 8; 4. 8; 4. 8	4. 8; 4. 8
	25 by 152		4. 5; 3. 0
	25 by 114	4. 8; 4. 8	4. 8
	25 by 102		4. 8
	25 by 76	4. 8; 1. 2	
Log 5	38 by 152	4. 8; 4. 8; 4. 8	4. 8; 4. 8; 4. 8
	25 by 152	4. 8	4. 8
	25 by 114	4. 8	4. 8; 3. 9
	25 by 102		
	25 by 76	4.8; 2. 1; 2. 4	1. 2
Log 6	38 by 152	4. 8; 4. 8; 4. 8	4. 8; 4. 8; 4. 8
	25 by 152		4. 8
	25 by 114	4. 8; 4. 8; 4. 2	3. 9
	25 by 102	4. 6	
	25 by 76	2. 1	4. 8

Log Number	Sawing pattern Dimensions mm	Sawn boards Length mm	Simulated boards Length mm
Log 3	38 by 152	4. 2; 4. 2; 4. 2	4. 2; 4. 2; 4. 2
	25 by 152	4. 2	4. 2 3. 6
	25 by 114	4. 2; 3. 9	2. 7
	25 by 102		
	25 by 76		3. 0; 3. 0
Log 7	38 by 152	4. 2; 4. 2; 4. 2	4. 2; 4. 2
	25 by 152	4. 2; 3. 9	3. 3
	25 by 114	2. 7; 3. 6	4. 2; 3. 3
	25 by 102		2. 7
	25 by 76	4. 2; 3. 6	0. 9
Log 8	38 by 152	3. 6; 3. 6; 3. 6	3. 6; 3. 6; 3. 6
	25 by 152		3. 3; 3
	25 by 114	3. 3; 3. 0	
	25 by 102	3. 6	2. 7; 1. 2
	25 by 76		3. 3; 3. 3
Log 9	38 by 152	3. 6; 3. 6; 3. 6	3. 6; 3. 6; 3. 6
	25 by 152	3. 3	3. 0
	25 by 114	3. 6	3. 6
	25 by 102	1. 2	
	25 by 76	2. 4; 2. 4	2. 4; 0. 9; 0. 9
Log 10	38 by 152	4. 8; 4. 8; 4. 8	4. 8; 4. 8; 4. 8
	25 by 152		4. 8
	25 by 114	4. 2; 4. 2; 4. 2	3. 9
	25 by 102	3. 3	1. 8
	25 by 76	2. 1	

The compared results of the two log classes highlight consistent but notable differences between sawn and simulated volume recoveries. This is mainly due to the differing board lengths of some simulated compared to sawmill sawn boards. The centre boards generated for the simulated logs vs sawn logs were similar, with differences emanating from the edge boards. This is expected since the simulation environment uses a more efficient and consistent optimizing system than the manually operated optimization edger at the sawmill. Difference between sawn and simulated board recoveries can be attributed to several factors. The relevant factors notable in this experiment are presented and discussed in the next subsections.

4.1.2.1 Possible reasons for the differences in volume recovery for the logs

4.1.2.2 Knots and external damage

External log damages do affect the quality of the resultant boards. Some of the boards with a high concentration of knots had to be thrown away as waste. Similarly, boards resulting from damaged part of the log shown in Figure 29, were of unacceptable quality. This will not affect the simulated volume recovery, however the sawn volume recovery of logs with knots or external damages will have lower volumes than expected. Only small logs exhibited large knots and external damage as reported in section 3.1 (Materials and Methods).

Figure 29: Damaged log showing properties which reduced its lumber yield.

4.1.2.3 Ovality measurements and log generation

The ovality position of the log was not measured. This could have resulted in ovality direction of the real-world log being in a different plane in Simsaw, compromising the geometry of simulated logs, hence volume recovery. For instance, an ovality of 0.9 and 1.1 is the same but in different planes.

It is also worth noting that the simulation environment is an ideal log model, therefore the results will be better

4.1.2.4 Operator error

There were a few cases where the logs were not positioned in the demarcated vertical position for the first sawing cut. This is shown by the skewed line on the centre boards as depicted in Figure 30. This could be attributed to the log slipping out of position whilst being fed into the primary saw. The simulated sawmill did not take this into consideration, this could have resulted in different log yield being realized.

Figure 30: Skewed orientation on sawn board insinuating the possibility of log slipping at headrig operator error

4.1.2.5 Mixing of the small boards

Most of the boards designated for edging or resaw were short and had colour only on one end. There could be a chance that some of the boards of the same colour were mixed during the board collation phase. This would make another log seem to have a higher volume recovery, whilst at the expense of another log of the same colour. Although the chances of such a mistake was very low, it was a possibility. However, this will not affect the mean volume recovery difference between sawn and simulated results.

4.1.3 Key observations summary

The sawmill benchmarking studies show that provided the same conditions, Simsaw 6 simulated sawmill results showed relatively good conformity to the sawn sawmill board recoveries. This underlines the predictability of volume recovery in a real-world sawmill production using Simsaw 6 simulation software.

For small logs, the software overestimated log volume by 1,4% to 2,4% with a mean of 1. 8% volume recovery overestimation. The software overestimated the real-world sawn logs volume recovery with between 1,3 to 3,7%, with a mean of 2,2% for large logs. For the small and large logs combined the simulation results were on average 2% higher than real sawn results.

To reduce errors whilst undertaking the comparative studies presented in this section, simulation validations were put in place. All simulated logs were based on real log measured characteristics. The sawmill's sawing patterns, board grading rules and wane specifications were also applied to the sawmill simulation therefore effectively mimicking the real-world processes.

The difference between simulated recovery and sawn log recovery of individual logs was relatively consistent around the means for the two log classes, thereby indicating the potency of Simsaw 6 simulation in comparative studies. Although the trial served its scope, improved trends could be attained using a larger sample size. As such, the results should be interpreted mindful of the logs sample size.

4.2 Sawmill Simulation: Random widths and wane edged boards

The results from the four simulation themes are presented and discussed in this section which essentially relate to the possibility to improve volume recovery by introducing random widths and increased wane allowance in a sawmill production process. It should be noted that the "real log" simulation option was selected for this study. This imply that differences between simulated results and actual sawmill results will likely be lower than determined in the sawmill study described in the previous section where the "real log" option could not be applied.

4.2.1 Volume recovery scenario comparisons

The following terminology and scenarios will be used in the text:

- SSP- Standard sawmill pattern volume recovery using the wane rules currently being used across major South African sawmills.
- RW- Random width volume recovery, using normal wane currently allowed in South African sawmills.
- IW–Volume recovery that can be obtained with increased wane allowance allowed.
- RW +IW –Volume recovery obtained from a combination of random widths at allowable increased wane allowance.

Results discussed in the following subsections focus on the scenario with the highest wane values, out of the 125 different possibilities simulated. Simulation scenario 1 in section 3.2.3. 3 Table 13 of wane (thickness 75%, width 50% and length100%) and highest volume recovery yield was adopted for comparison analysis. The volume recovery output will therefore be a single value for this scenario showing volume recovery per simulated log class. This assisted in gleaning objective insight on how each theme affects the sawmill yield using the SSP simulation platform as a benchmark.

4.2.1.1 Sawmill volume recovery using standard sawing methods (SSP)

The volume recovery from the SSP sawing scenario was used as the base case for standard sawmill output. SSP results show an increase in volume as the log diameter increases proportional to the log classes as represented in Figure 31 and explained in Figure 32. This can be attributed to geometrical factors; increased amount of lumber products that can be cut from a larger log compared to a small log, since the outer area or wane plays a relatively smaller role in larger logs (Li et al., 2015) (Bomark, et al., 2015) . Large-diameter logs are also less sensitive when positioning for cutting at the headrig, fitting of sawing patterns is also easier hence improved cutting precision (Shenga et al., 2017). Volume recovery ranged from 46,3% for the small log class up to 59,3% for the largest simulated log class.

4.2.1.2 Application of random widths (RW)

The random widths (RW) scenario shows improved volume recovery compared to the standard sawing pattern (SSP) which was used as the base case as illustrated in stacked graph in Figure 31. The RW values, show the incremental volume recovery attained using the RW scenario compared to SSP scenario provided the same wane specifications (thickness 75%, width 50% and length100%).

There was no noticeable change in volume recovery for the smallest log class, Class 1 of diameter 13-13,9 cm. A higher volume recovery shift of 4,5% was noted for Class 2 (thus a total volume recovery of 4,5 + 45,8%), comprised of small logs whose diameter ranged between 14 to 15,9cm. This might be attributed to the fact that the small logs do not allow wide sideboards and therefore very little options exist in terms of board width in any event.

RW showed improved volume recovery of 4,5%. Volume recovery increased gradually from 1,2% up to 2,8 as the log classes increased. Although the average increase in volume recovery from random widths (RW) is 2%, this presents a significant improvement in output for a large, small-log sawmill where 2% volume recovery increase typically translate to 4-5% increase in total product value created.

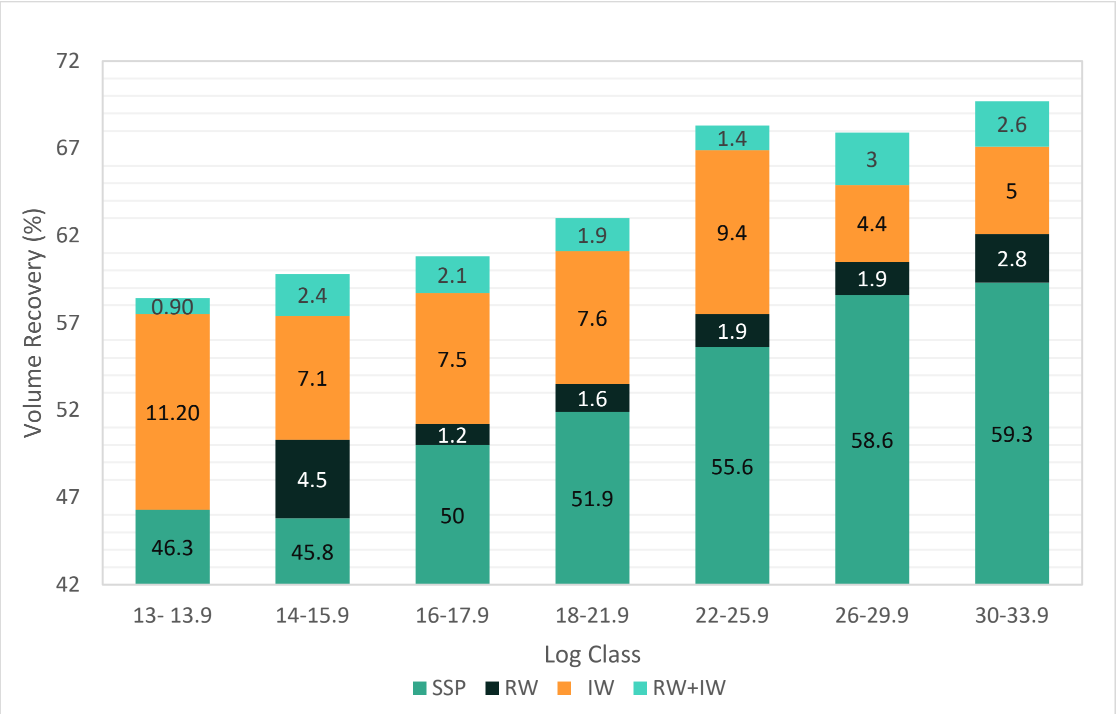


Figure 31: Simulated volume recovery of a standard sawmill and additional volume recovery possible using random widths, increased wane allowance and combined Random widths and increased wane allowance

4.2.1.3 Increased wane allowance (IW)

High improvements in lumber yields were noted from allowing increased wane allowance proportion on boards as depicted in Figure 31. Simulation sawing scenario with wane specifications (thickness 75%, width 50% and length100%) was also adopted in generating single values for the IW theme. Since the graph is stacked, comparisons in this section are made with respect to the change in volume recovery from RW to IW (the volume change from IW to SSP = SSP+ increment from RW+ increment from IW).

Across the seven log classes simulated, the volume recovery ranged from 57,5 to 67,1% as the log diameter increased. A significant jump in volume recovery of 11,2% was noted for the smallest logs class -Class 1, whose diameter ranged from 13-13,9cm. From log class 2 to log class 4, the increase in volume recovery remained fairly constant over 7%, marginally increasing up to diameter class 22-26,9 cm. A significant increase was noted from the 22-25,9cm diameter log class. The large log classes of 26-29,9 and 30-33,9 diameter showed lesser volume recovery increases of 4,4% and 5% respectively compared to the base case (SSP) theme. In general, there seem to be a decreasing trend of potential volume recovery increase from small logs to large logs. The areas marked 'reduced area' in Figure 32, highlight the focal zones of wane edges inclusion, leveraging on reduction of sawn-off waste material, resulting in improved yields from strategic sawing . Smaller logs have increased opportunity of improved lumber yield if more wane is allowed compared to larger logs, hence significant improvement in volume recovery was noticed in the smaller log classes.

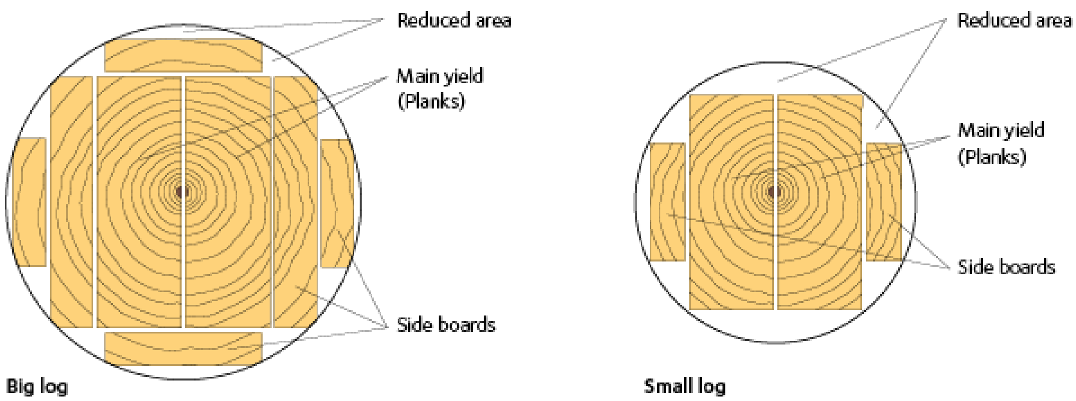


Figure 32: Interplay between log diameter and wane inclusion on lumber yield. Smaller logs pose increased opportunity of improved lumber yield if more wane is allowed

4.2.1.4 Increased wane combined with random widths (RW + IW)

The increased wane combined with random widths showed the highest simulated lumber yield, compared to the other scenarios. A 12,1% volume recovery increase was noted for the smallest log class, compared to the stanard sawing pattern (SSP) yield of the same class, and 0,9% higher than the IW volume recovery for the same log class. The volume recovery across the other six log classes is shown in Figure 31. They present a mean volume recovery increase of 11,49% over all the log classes. Akin to the IW scenario, smaller log class diameters generated higher increases in volume recovery compared to the larger log classes.

4.2.3 Overall sawmill recovery

A sawmill's total volume recovery is comprised of each log class's sawn lumber volume. In a big sawmill, the proportional contribution of the log classes to the sawmill's total volume recovery is often normally distributed. Small or large diameter logs represent a smaller proportion of the sawn logs whilst mid-sized diameter logs often make up the highest portion to the total volume of logs in a sawmill. A weighted average of each log class's volume recovery, based on the log class distribution of a sawmill, gives a proper indication of the overall sawmill output. In Figure 33 below it was assumed a sawmill had a log class distribution normally distributed as indicated in the table.

RW showed a 2% increase compared to the base case volume recovery of 52,5%, SSP went on to accrue a further 11% increase and lastly RW+IW resulted in a total 13% volume recovery increase as depicted in Figure 33. Based on the sawmill benchmarking study, one can assume that a real-world sawmill will have lower volume recovery compared to simulated results. Based on the benchmarking study, the standard sawing pattern results will likely be about 2.0% lower in a real-world situation and probably closer to (52,5% – 2,0%) = 50,5%. The additional volume recovery values through using random widths (RW) or increased wane allowance (IW) is also subject to operator errors in a real-world situation. However, it is likely that this can be reduced to a minimum by using commonly available equipment such as optimising edgers and trimmers.

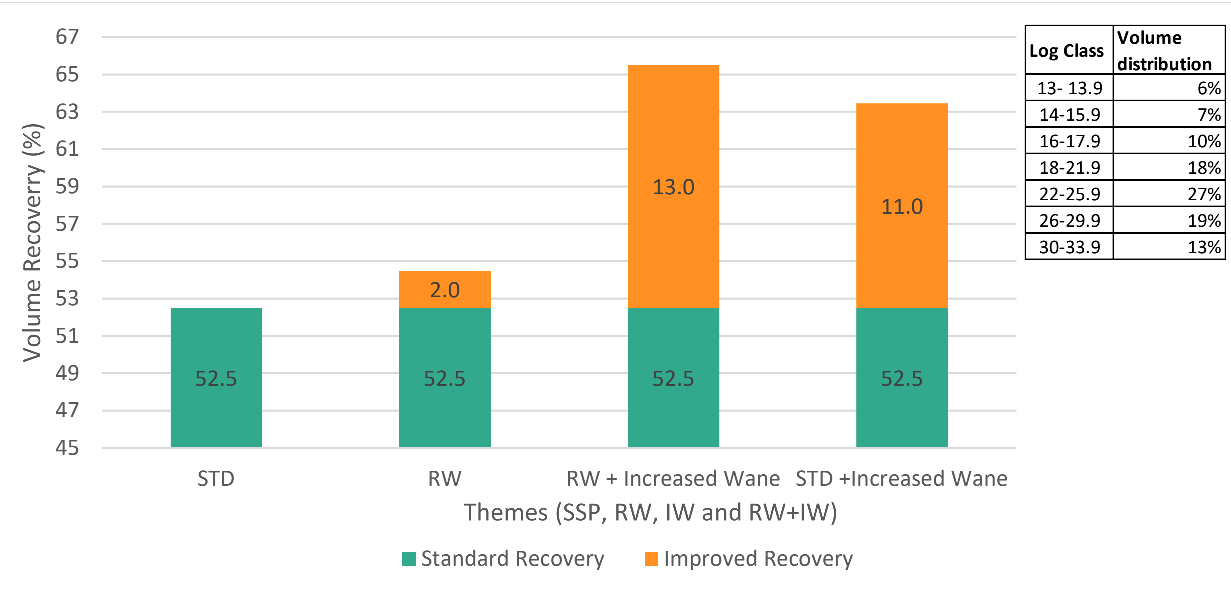


Figure 33: Weighted average volume recovery of the four simulated scenarios according to the weighting indicated. To get closer to real-world results values could be reduced by a further 2. 3% based on the sawmill benchmarking study.

4.2.4 Investigating the effect of different increased wane allowance scenarios

Different products can accommodate different levels of wane in terms of the percentage wane allowed in the thickness, width, and length direction. For CLT it is not clear at the moment what levels of wane can be incorporated in the product and therefore many wane scenarios were evaluated. The total 125 scenarios simulated are shown in Figure 34 and Figure 35.

They show the difference in volume recovery per each simulation scenario across the 125 simulations conducted. The RW+IW volume recovery values were 2,1% on average higher than the simulated (IW) volume recovery. This was expected since random widths (RW) exhibit a higher volume recovery than the standard sawing pattern (SSP), due to higher unit log utilization. Random widths offer improved sawing flexibility, hence higher volume recoveries.

4.2.4 Change in volume recovery per increased wane on the three axes

For further clarity, Figure 34 and Figure 35 show the influence of increased wane allowance across the three dimensions of a board for (SSP) and (RW+IW) are plotted over the 125 simulations conducted.

4.2.4.1 Definitions

A solid line running down represents constant width, with each color representing different widths considered in the simulation studies at 50,40,30,20 and 10%. Each of the 5 shapes represents wane considered lengthwise, from 20% to 100%. Constant length on the graph can be identified by simulation points having the same shape. The simulated data is presented at constant thickness intervals, ranging from 75 to 15%. To identify the influence of changing thickness on volume recovery, one would have to look at the same color lines or the shapes across different thickness values.

4.2.4.2 Trends

1. **Varied length**, at constant width and thickness (A look at the same shapes at a constant thickness can reveal the change in volume recovery induced by length at the same length and thickness wane parameters).

At constant thickness and length (change in volume recovery due to width can be tracked by the change in the shapes), the volume recovery increase is nearly linear at thickness =75. At this constant thickness of 75% and constant widths of 50,40,30, and 20% (lines going down), the volume recovery increases linearly with increase in lengthwise wane. A similar trend is seen at a thickness of 60%.

The linearity is observed up to lengthwise wane =80% at a thickness =60%, 45% and 30%; else a small increase is gained by lengthwise wane of 100%. A thickness 15%, and constant widths form 10% up to 50%, there is no significant improvement in volume recovery due to change in wane lengthwise. Therefore, a thickness of at least 30% could guarantee a maximum increase in volume recovery of 2%, which then doubles at 45% and then increases linearly for thicknesses of 60% and 75%.

At a constant thickness of 15% wane, and width, the increase of wane in length of up to 100%, will only yield a small volume recovery change of less than1%.

2. **Varied width** (change in volume recovery at same shape of simulated point across the different width % colors, at constant thickness and length).

As width increases volume recovery increases following a concave curve, implying a decrease in volume recovery change as width wane increases. This trend is the same, up to until a thickness of 15%, where the increase in width, however very marginal increases are noted.

For thickness of 45%, 30%, increases in width of 50% and 40% do not result in significant improved changes in volume recovery. At a thickness of 15%, there is also no notable change in volume recovery as width changes, such that these small changes even move to zero. It is also important to note that widthwise wane increase of 10% yields low changes in volume recovery.

3. **Varied thickness (**volume recovery changes from thickness variations at constant width and lengthwise wane)

The volume recovery varies linearly with increase at constant width and lengthwise wane =100%. This however ceases to be the same for lengths =80% up to 20%. The thickness still varies directly with volume recovery, however not exactly linearly.

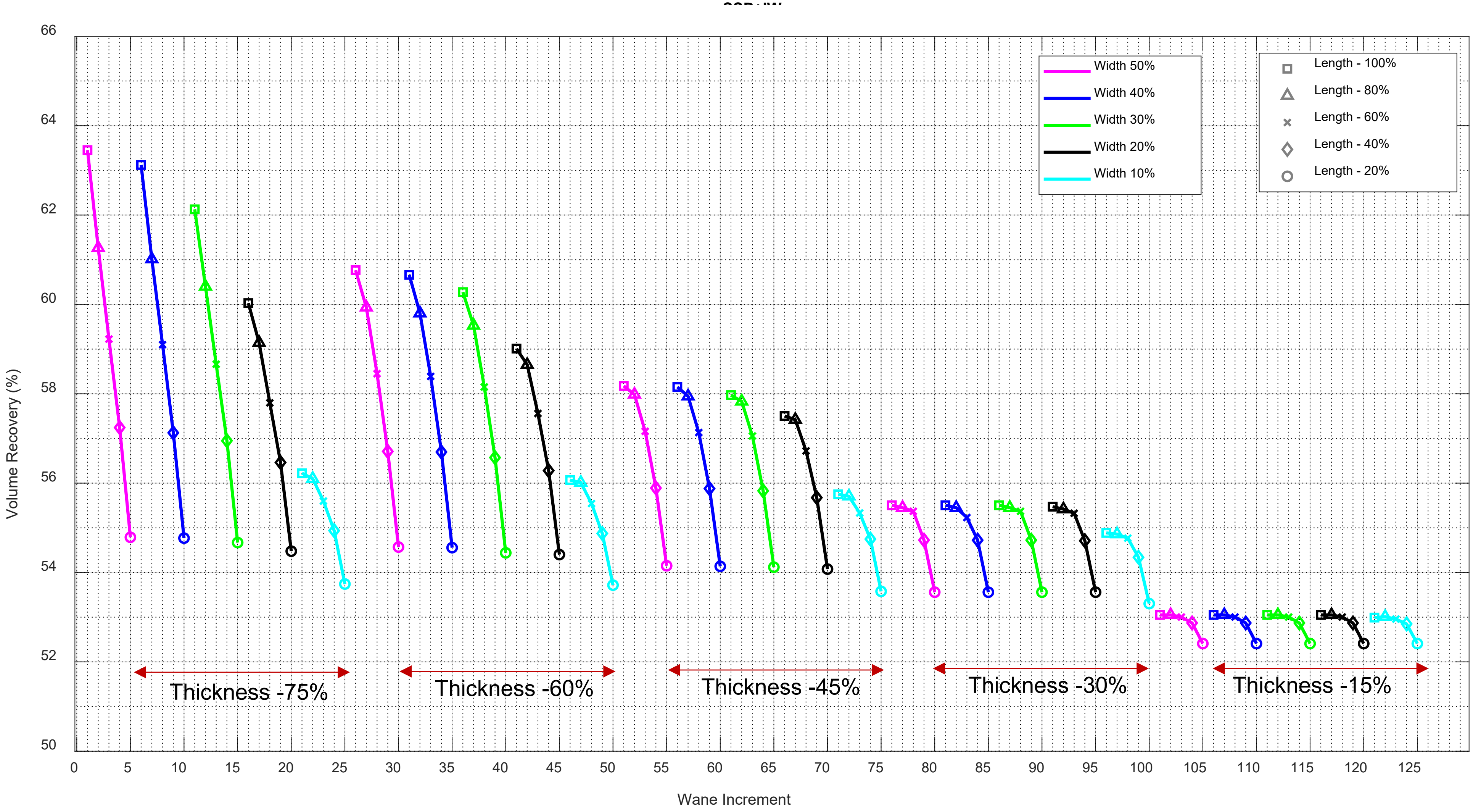


Figure 34: IW scenarios showing influence of allowed wane% in different axes on volume recovery

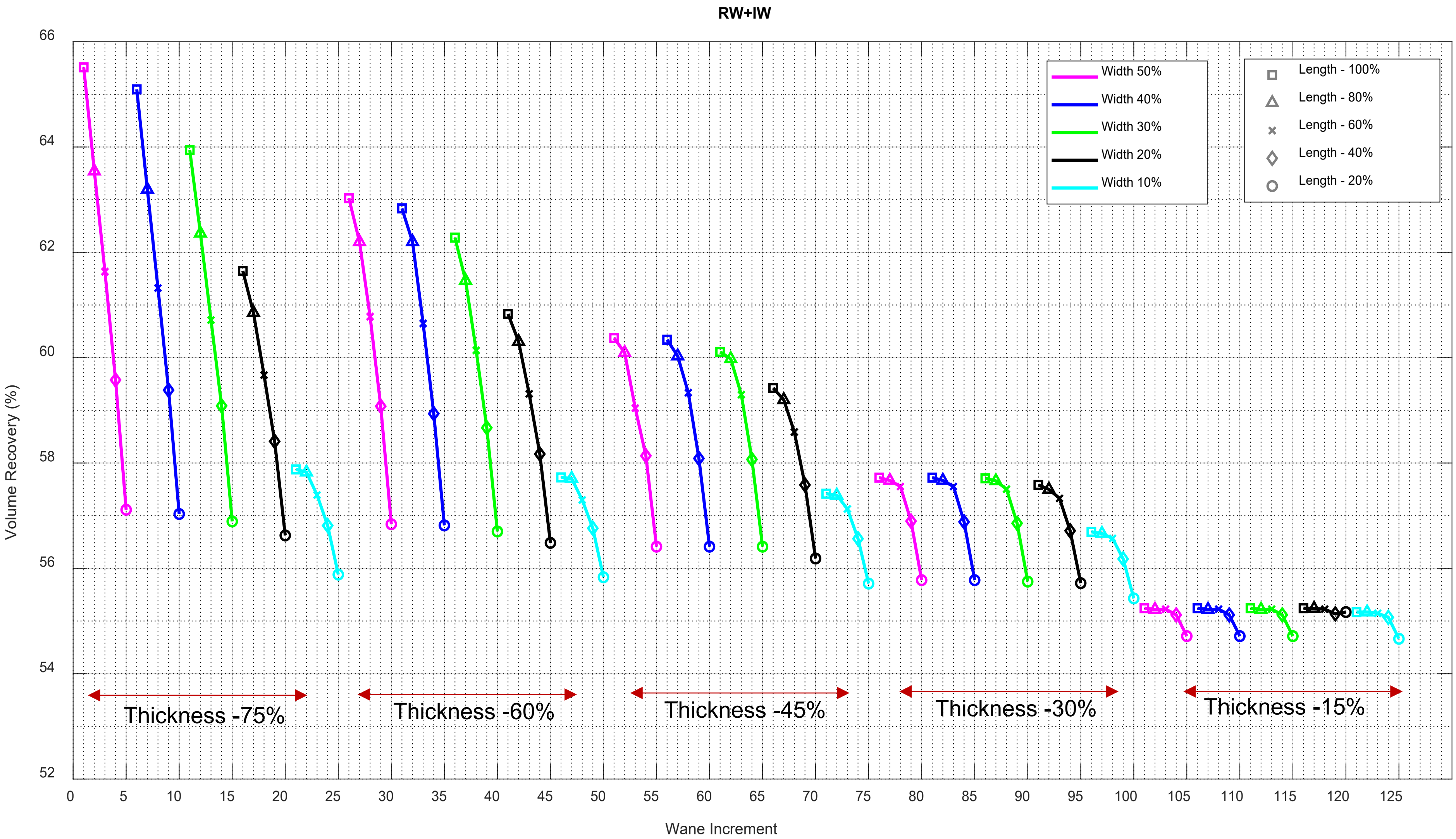


Figure 35: RW+IW scenarios showing wane % in different axes on volume recovery

4.3 Influence of wane on CLT stiffness and strength

This section presents the results of the mechanical properties of the CLT material where wane edged boards were tested in bending. The results of both bending and stiffness tests are also described.

4.3.1 Measured property of the CLT base materials

Wane category, board widths for the CLT middle layer, measured wane surface area on the middle layer, and wood density are detailed in Table 19. Mechanical properties of the CLT panel based on non-destructive a four-point bending tests are presented in Table 19.

The tested MOR values for the boards making the CLT outer layers are shown in Table 20, detailing the mean stiffness properties of each layer, mean of the top and bottom layers combined per each CLT panel and mean MOR per each of the three wane groups. Wane surface area of crosswise boards in the middle lamella of each CLT panel was used to categorise the boards.

Table 19: Measured physical and mechanical properties for the 10 CLT panels.

	Base material charactertics			Base material MOE (MPa)			Wane category
CLT panel no.	**Wane category**	**Wane surface area (%)**	**Input board widths (mm)**	**Top layer**	**Bottom layer**	**Combined mean for top and bottom layers**	**Mean MOE (MPa)**
1	Severe	26,5%	114	8973	6233	7603	7168
2		35,7%		7836	6222	7029	
3		27,3%		7278	6464	6871	
5		24,3%		9418	7283	8350	
10		22,3%	76	9069	7565	8317	
4	Moderate	14,1%	114	7377	7912	7644	7634
8		13,8%		9897	7655	8776	
9		13,3%		7548	9070	8309	
6	No wane	0		11183	7037	9110	8551
7		0		8815	7170	7992	

Most CLT panels within the severe wane category exhibited regions of higher concentration of knots in the bottom CLT lamella than other categories. The lower MOE values of some CLT panels in this category, could have been influenced by that.

4.3.2 Predicted vs. experimental CLT bending properties

It is not strictly correct to compare CLT bending strength to that of solid lumber since the middle layer has perpendicular grain direction. The experimental behaviour was therefore compared with predicted mechanical properties based on the shear analogy method for loads perpendicular to plane based on the global stiffness measurements. The shear analogy method is recommended for calculation of stiffness properties of CLT based on the single-layer properties (American National Standards Institutes (ANSI),, 2018)

Table 20: CLT predicted vs. experimental panel mechanical properties

CLT Panel no	Middle layer wane category	Density (Kg/m³)	Experimental bending Moment (FbS) (10^6) N-mm	Experimental EI (EI) (10^9) N-mm	Predicted EI (EI) (109) N-mm
1	Severe	495	10,6	56,2	52,0
2		559	8,5	59,1	48,8
3		531	7,2	50,8	54,4
5		542	11,0	61,7	60,1
10		508	10,9	61,5	51,3
	Mean		9,6	56,4	53,3
4	Moderate	566	12,6	56,5	58,0
8		530	10,3	64,8	60,6
9		541	10,1	61,4	62,8
	Mean		11,0	60,9	60,4
6	No wane	580	12,1	67,3	59,8
7		527	11,4	59,1	58,0
	Mean		11,8	63,2	58,9

The shear analogy model was then used to determine the theoretical bending strength for each panel, calculated using geometric properties of the CLT sections. Experimental bending stiffness EI of the solid CLT panel compared to the shear analogy predicted EI output value for each corresponding board as, well as S5 lumber constituted CLT as depicted in Table 20 and Figure 36 Both presents the comparison per wane category.

In general, it can be observed that the predicted EI value for most panels were fairly similar to the experimental results Figure 36. Panel 10 (severe group) and Panel 6 (no wane group) had relatively high deviations from the predicted results. Looking specifically at the results from the “severe wane” group, the presence of wane does not exhibit any negative influence in terms of panel stiffness. The comparisons between predicted and experimental results for the three groups, despite small sample size, can only be described as similar. The deviation from predicted values of all three groups seem to be in the same order of magnitude. From the results it, therefore, seems as if the levels of wane present in this study did not affect the panel stiffness. However, these results should be confirmed using larger sample sizes.

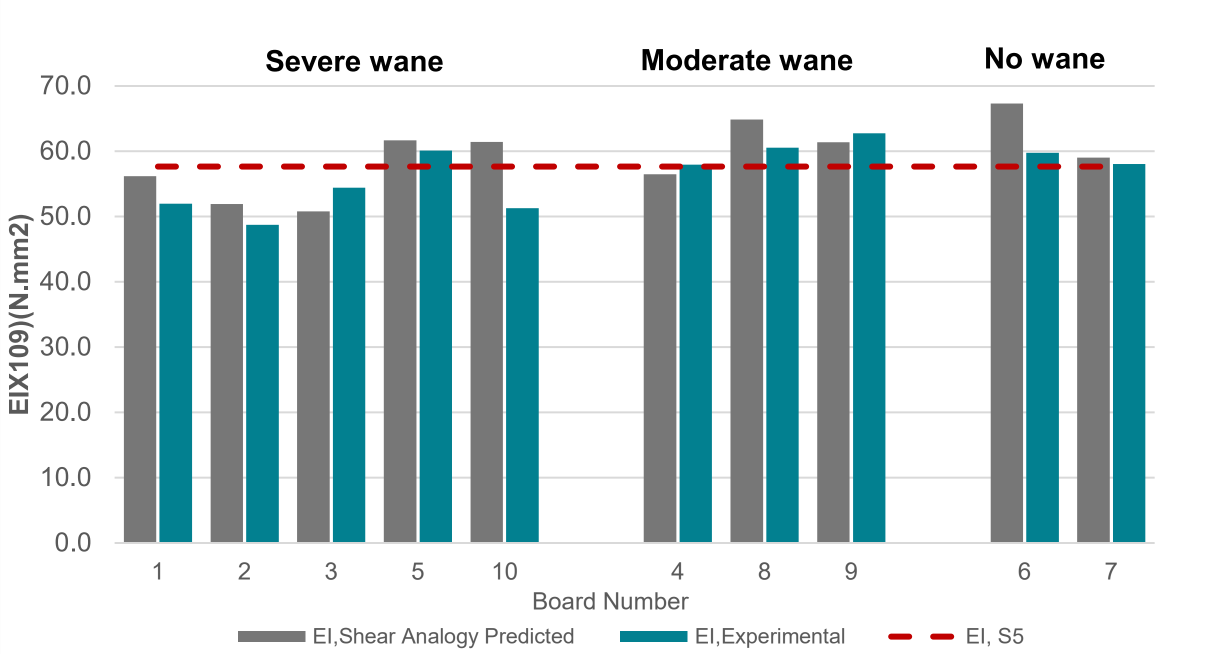


Figure 36: EI Experimental vs EI, shear analogy per individual board

The calculated experimental bending moment (FbS) results varied between 7.2 and 12.5 N. mm whilst the predicted bending moment for a S5 lumber based panel (FbS_{eff} =2.19 N. mm) is very low compared to the calculated values from the tested CLT panels. This is depicted in Figure 37 with the shear analogy predicted bending moment value illustrated by the red line on the graph.

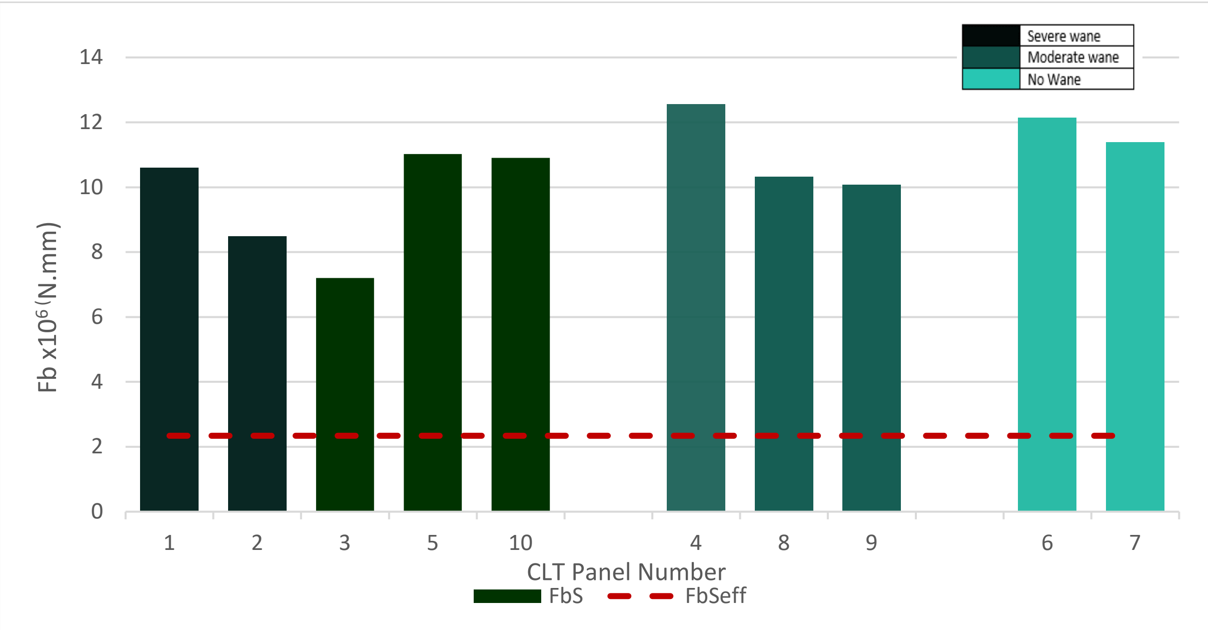


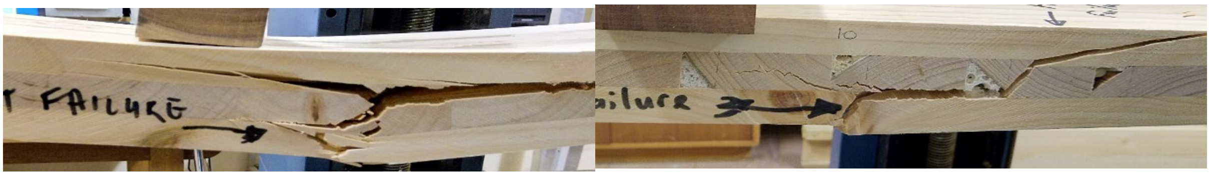
Figure 37: FbS values for the ten CLT panels per wane surface are category

The fact that all 10 panels peformed much better than the predicted FbS_{eff} based on grade S5 values is not that surprising. The load sharing effect that is part of CLT's inherent advantage as a product, probably played a role. Also, the relatively small sample size of 10 panels will also make low results improbable. However, of the five severe wane panels, two (Panels 2 and 3) had an FbS value lower than 10 N. mm/m. Of the five moderate and no-wane panels, none had values lower than 10 N. mm/m. The predicted and experimental EI of Panels 2 and 3 were relatively low (Figure 36) which normally imply that the bending strength will also be relatively lower. However, the FbS values for the same panels seem to be lower than expected. It, therefore, seems as if the severe wane possibly might have resulted in lower FbS values although this cannot be stated with certainty. A bigger sample would therefore shed more information. If the wane did indeed have an effect, the magnitude of this effect still seem to be fairly small since even the weakest panel (Panel 3) were three times higher than the predicted value. It is likely that the lower bonding area due to gaps caused by wane was responsible for the perceived lower FbS values.

According to the ANSI/APA PRG 320 (2018) standard, at least 80% of the surface area of a middle layer should be covered with adhesive. In the case of severe wane panels the wane area was between 22,3 –35,7% of the surface area (Table 19).These panels would, therefore, not have sufficient adhesive cover to satisfy this standard – an indication that more severe wane levels can have had an influence on the bending strength. Another possible effect of wane might be stress concentrations at wane areas due to the possibility of increased strain where wane gaps exist – view for instance the failure position of Panel 2 just below a wane gap (Figure 40, Appendix C).

4.3.4 CLT panels failure modes

The observed results showed that regardless of the wane surface area of the CLT middle lamella, the tested boards failed primarily in regions where big knots manifested. A sideview of the CLT panels Figure 38 and Figure 39 details this incidence. The failure modes in all the ten CLT samples are depicted in Appendix C and D. The prominent failure mode of the bending tests was the brittle tension failure, ensuing in the CLT bottom longitudinal layer.



(a) (b)

Figure 38: Bending failure manifesting in areas positions containing big knots

Figure 39: Big knot at the bottom exhibiting a weak point

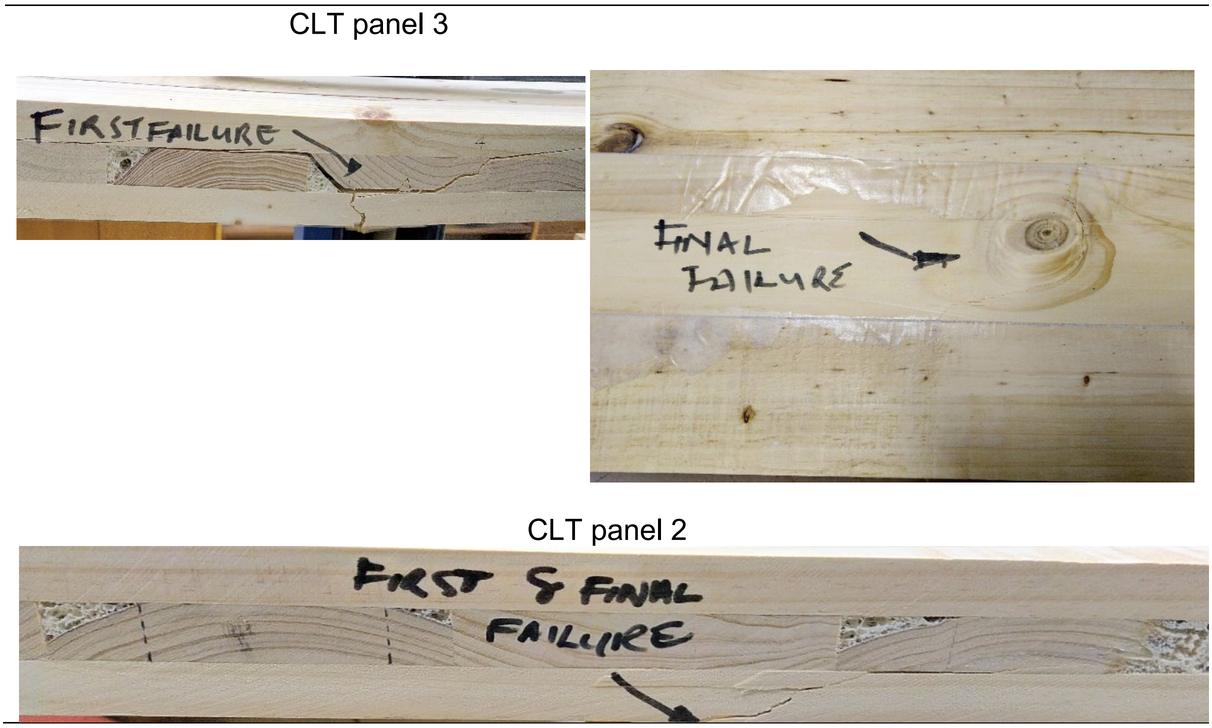


Figure 40: Failure modes in CLT panels 2 and 3

Of particular interest is the failure modes of Panels 2 and 3 – the two panels that failed at lower FbS levels than others as seen above in Figure 40. Panel 3 exhibit shear failures around wane areas where a smaller shear area resulted from wane gaps - a clear indication that wane possibly played a role in the lower FbS value of this panel. Panel 2 failed below a wane gap. This could perhaps be the result of initial stress concentration on the compression side of panel where a wane gap existed.

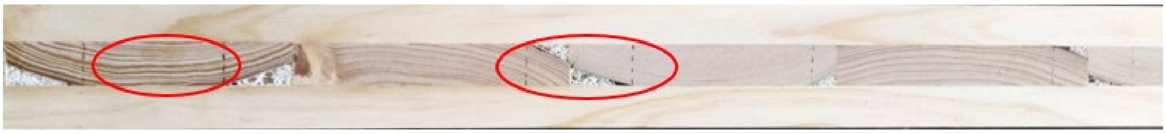
4.3.4 The effect of knot characteristics on the CLT strength properties

The sum of measured diameters was expressed as a percentage of total board width and a stretch of 150 mm width wise, within the centre of the CLT panel.

The measured knot properties were correlated with the MOE and MOE values; however, no significant correlation was noted. This is the advantage of laminated and engineered timber where defects are dispersed over the volume of material. Hence a load sharing effect remove the typical influence of large defects that is experienced in structural lumber.

4.3.5 Salvaged volume

The lengthwise side view of the manufactured CLT panels shows the exess wane that was included in the CLT manufacturing. The shaded area depicted in Figure 41 . (a) and (b) shows the parts that would have been cut off as excess waste in a normal sawmill operation. However, value added CLT mafacturing, fosters increased opportunities for the utilization of wane edged lumber. From a sawmill perspective, this translates to increased lumber yields.


(a)


(b)

Figure 41: CLT Panel side view showing sections of incorporated wane

The length of each individuel excess wane pocket widthwise of the CLT panel,,was measured and summed. This waste lumber recovered accounted for as much as 26**%** of the lumber used within the middle lamella. Individual lumber recoveries per length of each CLT panel are shown in Table 21. The width of wane was measured to the nearest 1 mm and the sum of the lengths of wane to the nearest 10 mm as per EN Standards.

Table 21: Excess wane included in the middle lamella, along the CLT panel

Board Number	1	2	3	5	10	4	8	9
Summed Length (mm)	683	859	608	598	553	475	398	283
Excess wane (%)	32,5%	40,9%	29,0%	28,5%	26,3%	22,6%	19,0%	13,5%
Category	*Severe wane*					*Moderate wane*		

Observations from Table 21 and Figure 41**.** Indicates that the CLT manufacturing with increased wane allowance boards resulted in high utilization of lower value lumber, therefore increased value extraction per single log.

The wane edges allowed in this study showed that on average more than 25% and up to 40.9% of the length can have wane present. This can have a profound effect on the conversion efficiency of logs to final CLT products.

4.4 Integrated CLT manufacturing

This section discusses the integration of results and the potential for industrial implementation. To effectively leverage economic benefits from raw material utilization, it is imperative to integrate and optimize the wood processing value chain (Pinto et al., 2002). Interlinked CLT value chain processes addressed in this research were:

1. Improved volume recoveries through sawmill optimization. This was facilitated by allowing lower value lumber (containing higher levels of wane) and process adaptation (allowing non-standard random widths).
2. Utilization of lower value, wane containing lumber in CLT crosswise lamellas, translating to improved revenues for the sawmill.
3. Testing of the CLT panels containing lower value, wane containing lumber. This validated the structural integrity of the CLT products.

4. Reduced CLT manufacturing costs; implying a direct proportional decrease in CLT selling prices.

Answering of the two overarching research questions in tandem facilitates an integrated optimization and decision-making process. To provide a perspective that could support the operationalising of this research, this chapter both contextualises and conceptualises key functional areas, merits, and drivers across the CLT production value chain.

4. 5 Value chain optimization opportunities

Optimizing activities cross the sawmill value chain individually may lead to optimum solutions that are not all-inclusive. To attain globally optimum results, the operations should be examined from an end-to-end perspective (Usenius 1996); (Stängle et al., 2015).

To effectively utilize raw materials for maximised economic yields, the integration of the lumber value chain is also imperative as is the optimization of the different individual constituents (Pinto et al., 2002). As such, an integrated sawmilling and CLT Process would therefore mitigate the challenges that lie in optimizing only one part of the sawmill value chain system.

Some of the opportunities of the value chain integration are discussed in Table 22. It provides a perspective on how optimized value chain integration can be conceptualised by unpacking the interplay between value added CLT manufacturing and sawmill optimization.

Table 22: The potential of an integrated value addition CLT value chain.

Value chain Functional Area	Requirements	Opportunities	Questions addressed by this research
Sawmill products optimization	• Optimizing raw materials	• Improved revenues • Improving volume and value recovery • Reduced end to end value chain risks	• What could be optimal log cutting options? • Improved log utilization translating to higher revenues
	• Need to improve volume recoveries since logs are very expensive • No market for low value lumber • By products chips, sawdust, and bark being sold for low prices	• Flexible sawing patterns that include more low value lumber, whilst reducing waste • Improved control on location of higher-grade lumber in a product for better structural properties	• What alternatives products that can uptake the low value lumber? • Is it beneficial to produce low value lumber?

Value added product -CLT Manufacturing	• Reduce CLT manufacturing costs • Improve CLT adoption • Find wood resources for CLT manufacturing	• Use of low value lumber for some layers of the CLT panel • New employment opportunities in CLT manufacturing • Sawmill production can optimize to include this	• What alternative materials can be used in CLT that could reduce the price per unit? • Is the manufactured CLT structurally strong?

4.6 Translating simulated volume recovery to real world sawmill yields

The maximum wane permitting scenario (thickness =75, width =50 and length =100%), previously discussed, and illustrated in Table 23, is used to illuminate interpretation of simulated to real-world yields. As discovered in Section 4.1, the sawmill simulation benchmarking results, deduced that the Simsaw 6 software overestimates the volume recovery of a real-world sawmill by 2.0%. The weighted volume recovery values for each scenario in Table 23 would therefore be extrapolated two percentage points lower to attain the approximate real sawmill values.

Table 23: Wane combination scenarios informing sawmills of potential increased recovery

Theme	**Wane combination scenarios**		
	High Wane% *(Thickness, Width, Length)*	Medium Wane% *(Thickness, Width, Length)*	Low Wane% *(Thickness, Width, Length)*
SSP	75,50,100	60,40,100	45,30,100
Weighted volume recovery (%)	61,5 (63,5-2) %	58,7(60,7-2) %	56,1(58,1-2) %
RW+IW	75,50,100	60,40,100	45,30,100
Weighted volume recovery (%)	63,5 (65,5-2) %	60,8 (62,8-2) %	58,2 (60,2-2) %

Each log class's contribution to the sawmill's volume recovery was calculated with class1 contributing 6%, class 2; 7% class 3; 1%, class 4; 18% class 5; 27% class 6; 19% and class 7; 13% respectively. The possible real-world yields of a sawmill using the (75, 50,100) % wane combination scenarios are:

- The highest log volume recovery per log individual class would therefore be 67,63% (69. 7- 2,07) from the (IW+RW) theme; with a corresponding highest weighted average volume recovery of 63,43% (65,5- 2,07) across the seven log classes
- (IW) scenario's highest volume recovery is 62,96% (67,1- 2,07). The weighted average volume recovery would be 61,43 % (63,5- 2,07)respectively.

The limitations of wane size reported in national standards on visual strength grading led to a high number of rejected sawn timber. The development of markets has been largely regarded as a constraining factor to value-added agricultural products. (Best et. al, 2002). Improved log value utilization is a platform for mass timber growth in South Africa. The use of low value lumber in CLT, presents an opportunity for sawmills to be more flexible and inclusive in terms of sawing patterns. This translates to increased lumber revenues from a sawmill perspective and buttresses opportunities for CLT adoption and impact.

Chapter 5: Conclusions and recommendations

5.1 Conclusions

This chapter presents the findings of this research, which sought to establish ways of reducing CLT costs through value chain integration. The possibility for an integrated, value added CLT manufacturing plant was investigated and validated. This was facilitated by sawmill simulation optimization, leveraging on wane specifications flexibility. The sawmill simulation and CLT production were both validated through real world experiments. The overarching research objectives are addressed by the following conclusions.

5.1.1 Research objective 1: *To evaluate the potential increase in volume recovery when a SA Pine sawmill include random widths and increased wane allowance in its sawing strategy.*

5 1.1.1 Sawmill benchmarking trial

From the results, it can be concluded that Simsaw 6 simulation software fulfils the basic requirement of sensitivity meaning that a simulated sawmill model will likely give similar results. The software overestimated the log volume recovery at a mean of 2,07% compared to sawn volume for small logs.

It can be concluded therefore that the Simsaw 6 simulation program closely simulates a real-world sawmill environment as evidenced by the generated volume recovery results, at a mean overestimation of 2,01 % for small logs and the 2,13% for the large logs respectively.

5.1.1.2 Improved wane and random widths scenarios

The study demonstrated the huge potential in standalone increased wane (IW) and increased wane plus random widths (IW+RW) to improve volume recovery. The simulated scenarios of these two themes registered volume recovery of at least 57% in small log classes. Medium log volume recoveries varied from 58,7 to 63%, whilst larger log classes exhibited higher volume recoveries of up to 69%, for the highest wane permitting scenario.

Maximum mean weighted volume recovery for a typical small-log sawmill was 63.5% for the increased wane combined with random widths scenario (IW+RW), followed closely by increased wane (IW) scenario at 61.5 % respectively. These volume recovery results indicate very high improvements compared to the current volume recoveries attained in typical sawmills in South Africa.

5.1.2 Research objective 2: *To investigate the effect of increased wane allowance on SA Pine CLT strength and stiffness performance.*

5.1.2.1 CLT Manufacturing and testing

Highlights from bending tests of the ten CLT boards of varying crosswise lamellae wane surface area were are presented.

1. Bending stiffness

Comparisons between the predicted and experimental bending stiffness EI, mean per each wane group implies that increased wane did not seem to influence the bending stiffness of CLT panels.

Across all the categories however, the mean MOE of base materials had a predictable influence on the bending stiffness on a CLT panel. Panel 10 (severe group) and Panel 6 (no wane group) had relatively high deviations from the predicted results. Boards with wane seemed to fail due to the low MOE's of the base materials, significantly in the lower lamella.

- The inclusion of wane did not compromise CLT mechanical properties. This suggest that in the presence of structurally good base materials at the top and bottom of the CLT lamella's, overall stiffness properties of CLT panels containing wane in the middle layer are not compromised.

- The deviation from predicted values of all three groups are in the same order of magnitude. The inclusion of substantial wane percentage of up to 35,7% in CLT middle layers did not influence the bending stiffness of the CLT specimens.

2. Maximum bending moment

The results suggest that CLT manufactured from wane edged boards in the crosswise lamellas is mechanically sound and can easily make the expected requirements for CLT from the specific grade used. However, from the limited results obtained, it seems if the wane possibly did lower the bending strength of individual severe wane panels compared to moderate and no-wane panels, of the five severe wane panels, two had an FbS values lower than 10 N. mm/m.

- The magnitude of this effect still seems to be minimal as seen in the weakest panel (Panel 3) where it's bending strength is three times higher than the predicted value. It is likely that the lower bonding area due to gaps caused by higher wane surface areas of between 22,3-35,7% was responsible for the perceived lower FbS values.

3. Value chain optimization

The maximum wane permitting scenario of wane (thickness =75%, width =50% and length =100%), would result in the possible weighted single value real world sawmill recovery of 61,2% using the (IW+RW) and 60,7% with (IW). This improved wood volume can be harnessed in an integrated CLT plant to make low value lumber incorporated CLT panels.

Analysis of the results from the destructive tests conducted on the ten 3-layer CLT panels fabricated with wane edges boards, demonstrates their ability to deliver acceptable mechanical properties.

This validated experimental work undertaken in this research, attests its relevance in cementing the drive towards development of value added CLT manufacturing from wane edged boards. As such, value chain integration seems to hold much potential to reduce the cost of CLT in South Africa.

5.2 Envisaged impacts of research

This study successfully investigated and validated increases in sawn lumber recovery from flexible sawing. It then demonstrated the use of low value sawn lumber in CLT manufacturing and tested the strength properties of CLT made from wane edged boards within the transverse layer.

Application of the first objective of this research could realise substantial increase in volume recoveries within the sawmilling industry. Since there is no literature available on this topic, it would aid in decision-making and support overall sawmilling strategy.

Driving the overarching research aim of this research could improve adoption and scaling of CLT as a product due to reduced prices, translating to improved revenues through enhanced opportunities from a sawmill and the CLT manufacturing perspective.

Conclusively, the results illuminate resource utilization which is key to supporting the expansion of sustainable building and competitiveness will be improved.

5.3 Recommendations

Future research should focus on real world testing of wane and random width inclusion in a sawmill study (based on the simulated input values used here). Full sized CLT panels should be manufactured from the wane boards and tested for adherence to the specifications of a standard such as SANS 8892.

- In the longer term, new product types from wane boards and/or random widths should also be explored.

- Since the sample size was small, it is certainly an area that will need more research attention to fully benchmark the thresholds in the application of wane edged boards in CLT crosswise lamellas. A bigger sample size of CLT panels would be required, with a similar mean stiffness for each panel to explore the topic further.

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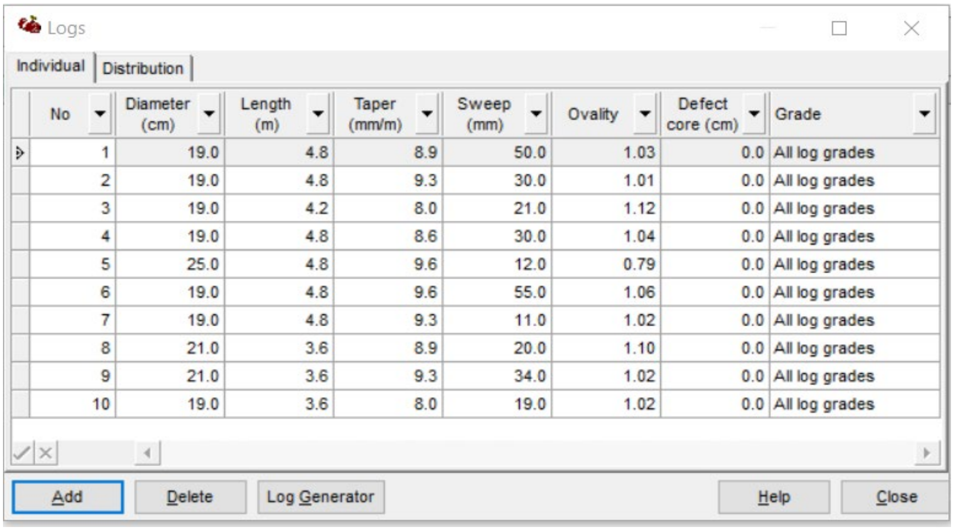
Appendices

Appendix A

Benchmarking Trial Simsaw 6 files

The Simulated Simsaw 6 specifications for the benchmarking trial are depicted in this section.

1. **MTO Small logs generation**

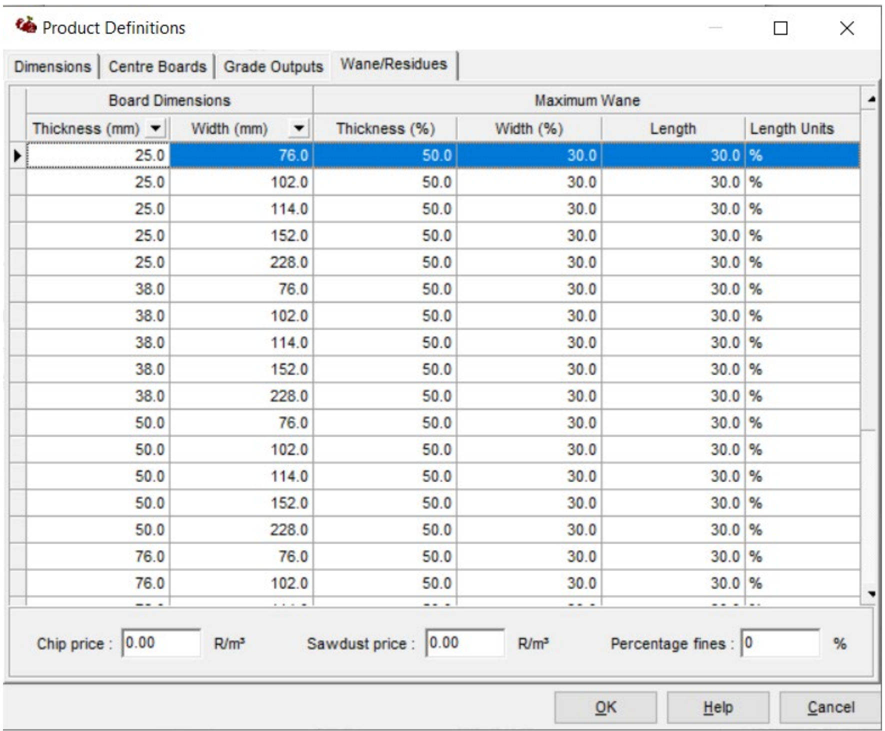

Logs

Individual | Distribution

No	Diameter (cm)	Length (m)	Taper (mm/m)	Sweep (mm)	Ovality	Defect core (cm)	Grade
1	19.0	4.8	8.9	50.0	1.03	0.0	All log grades
2	19.0	4.8	9.3	30.0	1.01	0.0	All log grades
3	19.0	4.2	8.0	21.0	1.12	0.0	All log grades
4	19.0	4.8	8.6	30.0	1.04	0.0	All log grades
5	25.0	4.8	9.6	12.0	0.79	0.0	All log grades
6	19.0	4.8	9.6	55.0	1.06	0.0	All log grades
7	19.0	4.8	9.3	11.0	1.02	0.0	All log grades
8	21.0	3.6	8.9	20.0	1.10	0.0	All log grades
9	21.0	3.6	9.3	34.0	1.02	0.0	All log grades
10	19.0	3.6	8.0	19.0	1.02	0.0	All log grades

Add | Delete | Log Generator | Help | Close

Figure A1: Small log -lol generation parameters


Product Definitions

Dimensions | Centre Boards | Grade Outputs | Wane/Residues

Board Dimensions		Maximum Wane			
Thickness (mm)	Width (mm)	Thickness (%)	Width (%)	Length	Length Units
25.0	76.0	50.0	30.0	30.0	%
25.0	102.0	50.0	30.0	30.0	%
25.0	114.0	50.0	30.0	30.0	%
25.0	152.0	50.0	30.0	30.0	%
25.0	228.0	50.0	30.0	30.0	%
38.0	76.0	50.0	30.0	30.0	%
38.0	102.0	50.0	30.0	30.0	%
38.0	114.0	50.0	30.0	30.0	%
38.0	152.0	50.0	30.0	30.0	%
38.0	228.0	50.0	30.0	30.0	%
50.0	76.0	50.0	30.0	30.0	%
50.0	102.0	50.0	30.0	30.0	%
50.0	114.0	50.0	30.0	30.0	%
50.0	152.0	50.0	30.0	30.0	%
50.0	228.0	50.0	30.0	30.0	%
76.0	76.0	50.0	30.0	30.0	%
76.0	102.0	50.0	30.0	30.0	%

Chip price : 0.00 R/m³ Sawdust price : 0.00 R/m³ Percentage fines : 0 %

OK | Help | Cancel

Figure A2: Small log -product definitions

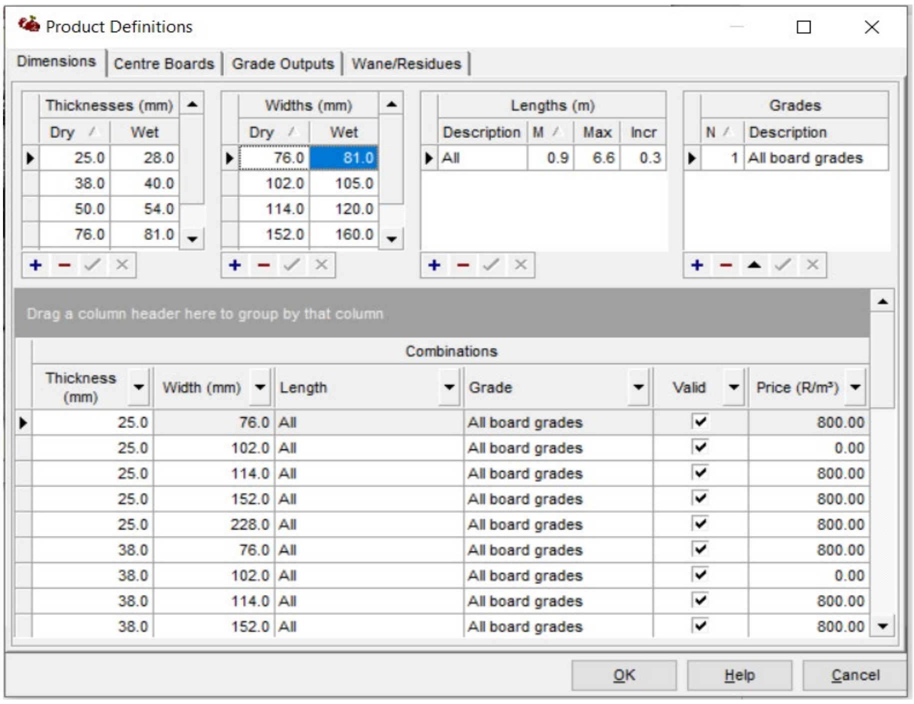


Figure A3: Small log -product definitions

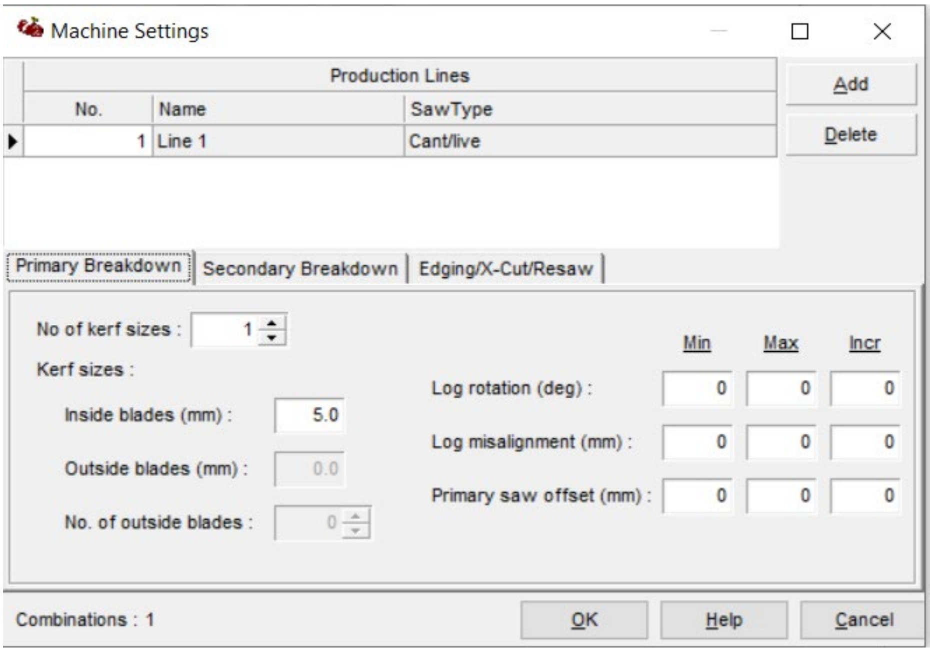


Figure A4: Small log-machine settings

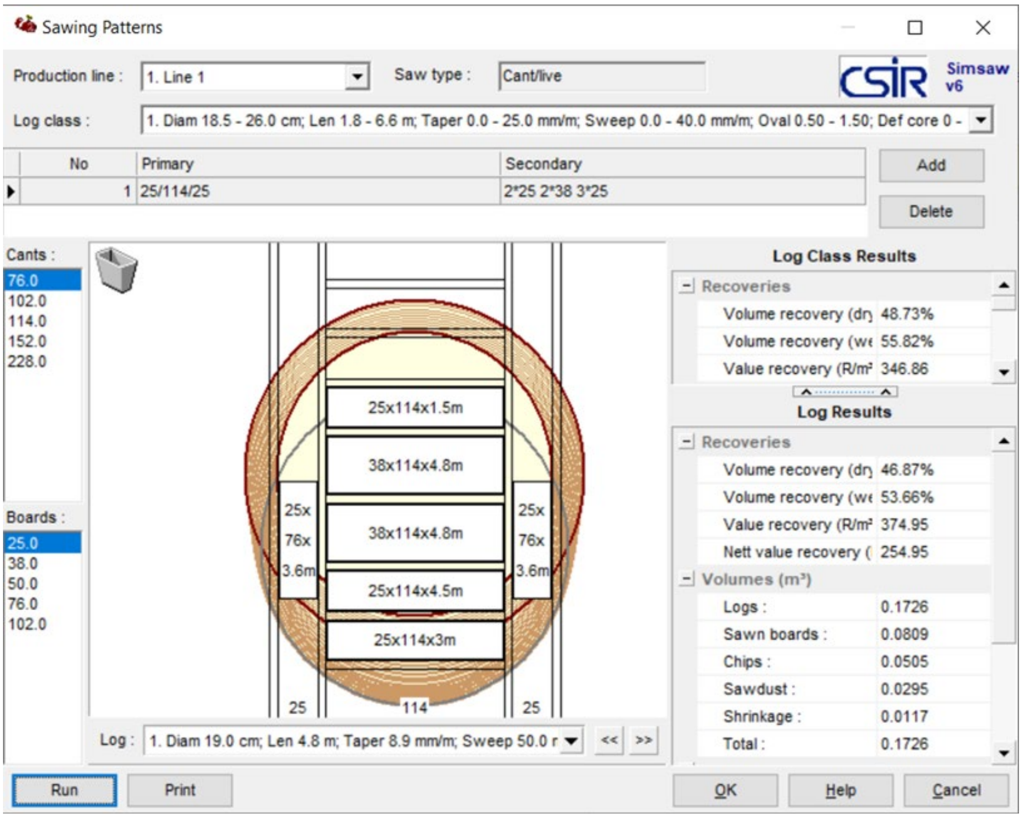
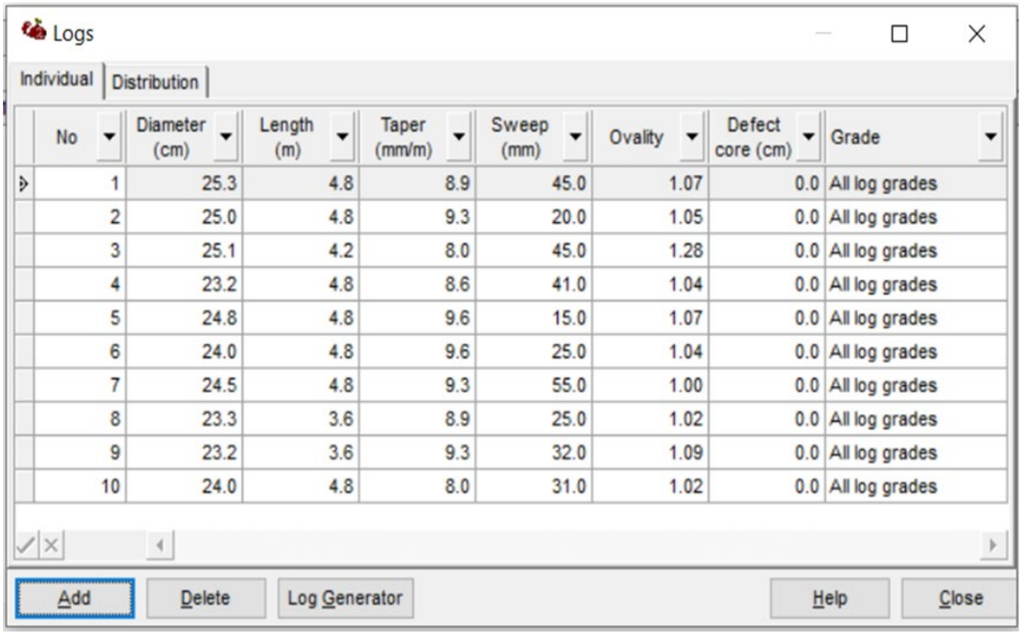


Figure A5: Machine settings

2. MTO Large Logs



No	Diameter (cm)	Length (m)	Taper (mm/m)	Sweep (mm)	Ovality	Defect core (cm)	Grade
1	25.3	4.8	8.9	45.0	1.07	0.0	All log grades
2	25.0	4.8	9.3	20.0	1.05	0.0	All log grades
3	25.1	4.2	8.0	45.0	1.28	0.0	All log grades
4	23.2	4.8	8.6	41.0	1.04	0.0	All log grades
5	24.8	4.8	9.6	15.0	1.07	0.0	All log grades
6	24.0	4.8	9.6	25.0	1.04	0.0	All log grades
7	24.5	4.8	9.3	55.0	1.00	0.0	All log grades
8	23.3	3.6	8.9	25.0	1.02	0.0	All log grades
9	23.2	3.6	9.3	32.0	1.09	0.0	All log grades
10	24.0	4.8	8.0	31.0	1.02	0.0	All log grades

Figure A6: Large logs -lol generation parameters

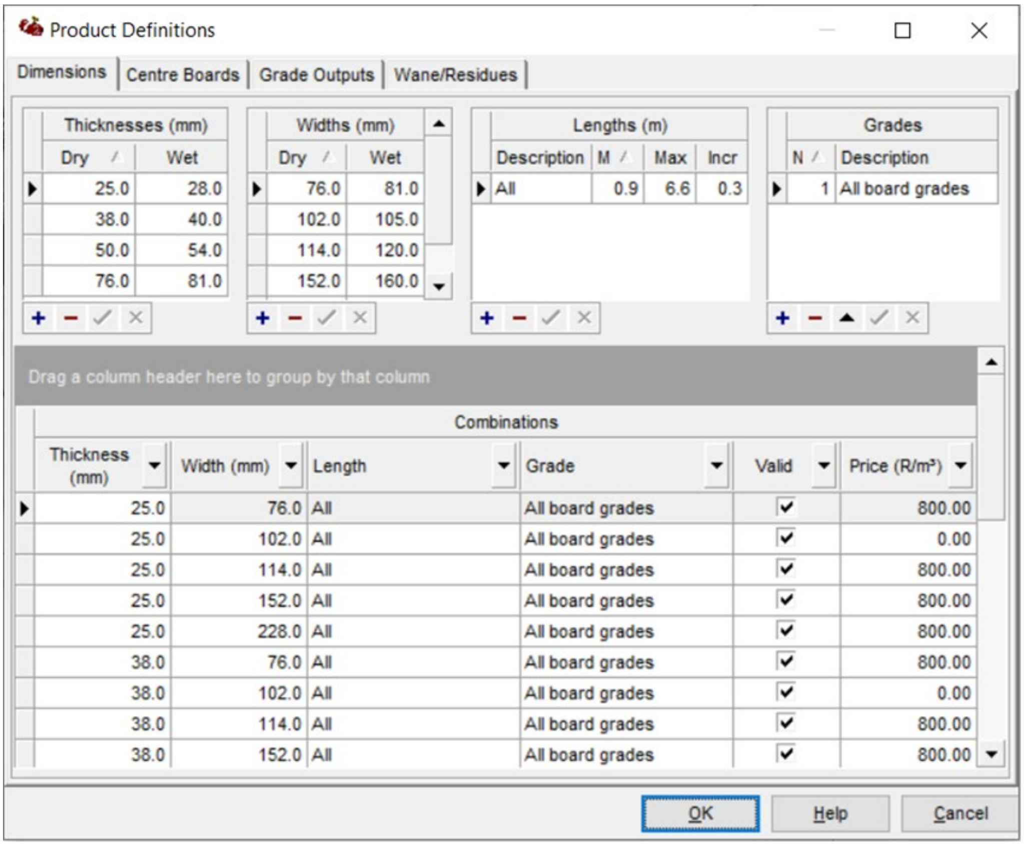


Figure A7: Shows the user interface of Saw2003.

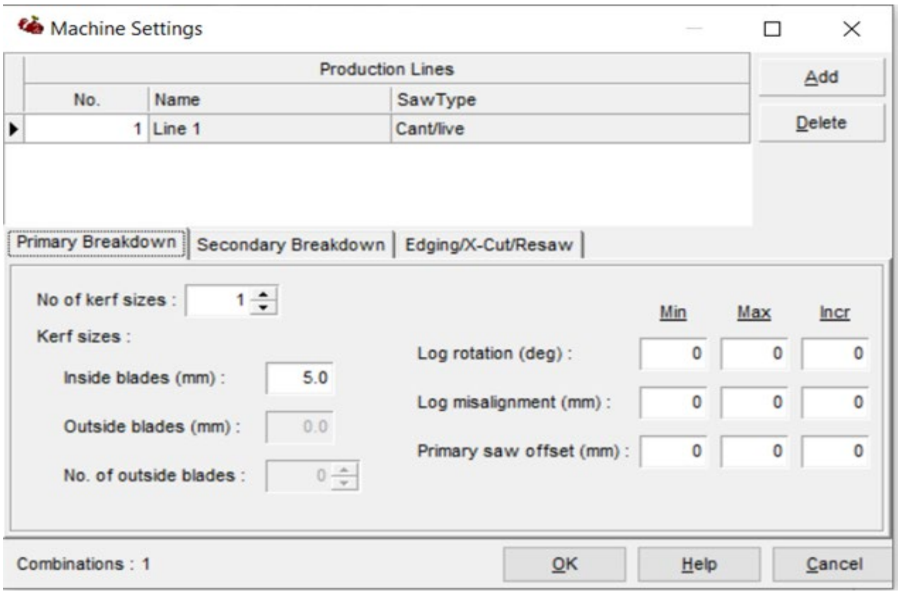


Figure A8: Large logs -Machine settings

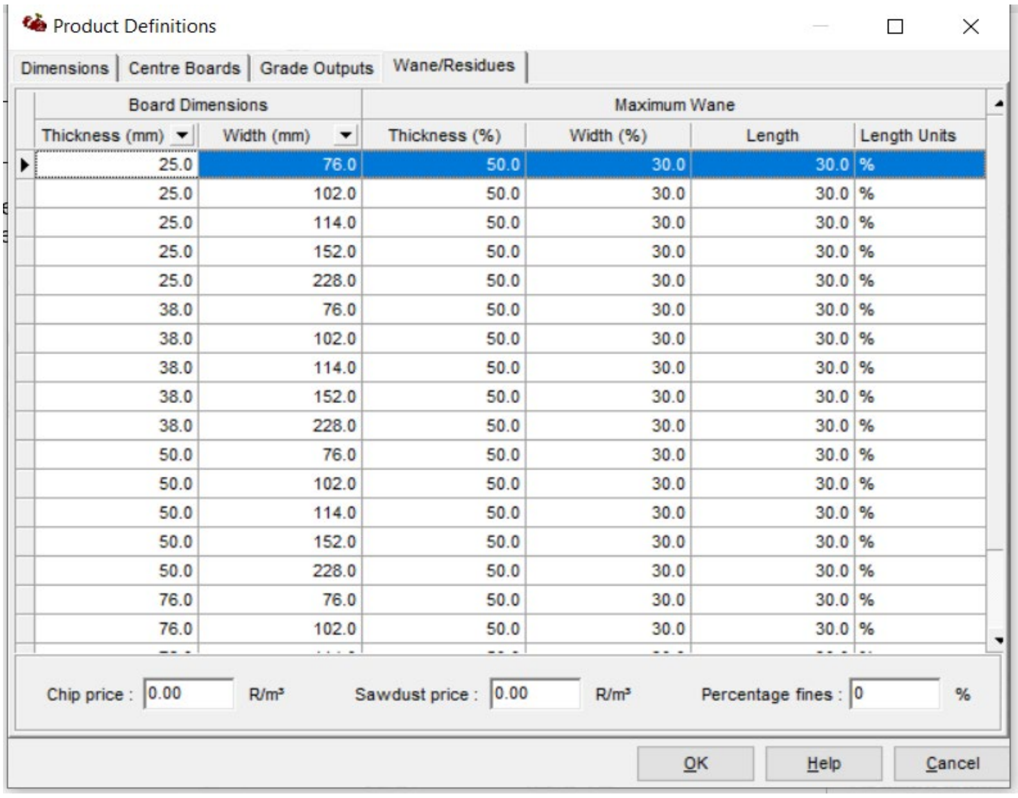


Figure A9: Large logs -Product definitions

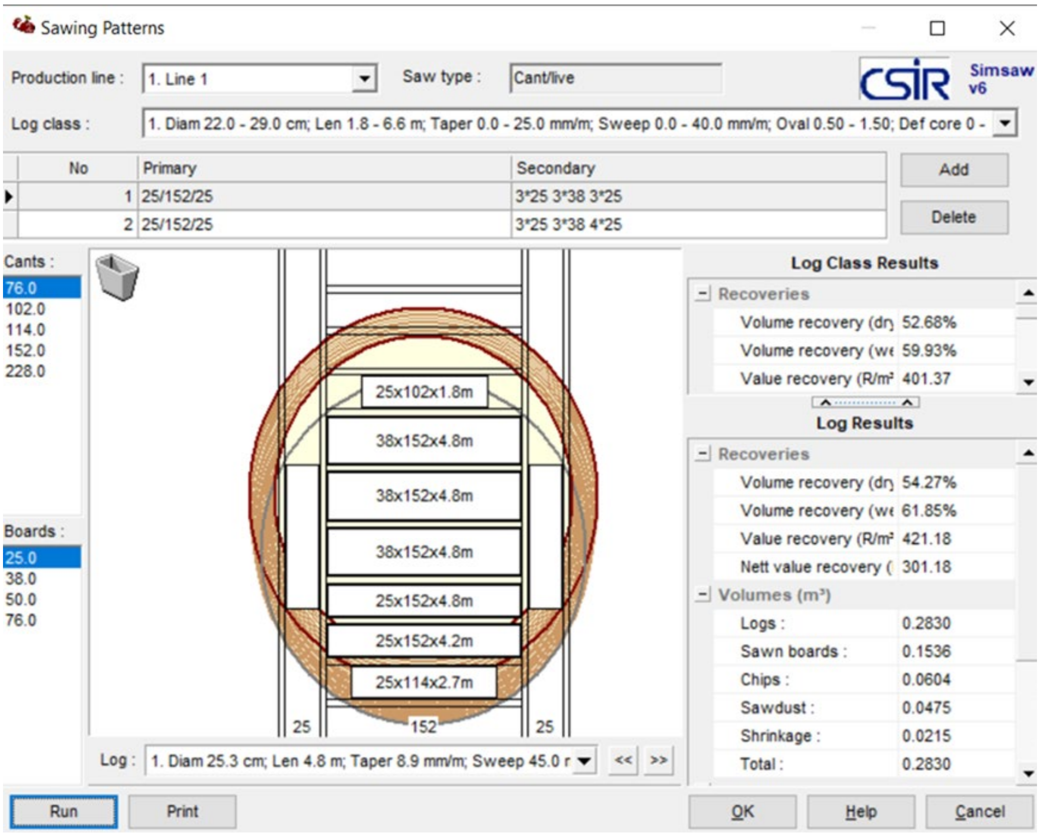


Figure A10: Large logs -sawing patterns

Appendix B

This section details the simulation steps taken in Chapter 3. 2 (Sawmill simulation). The volume recovery from different combinations of wane was investigated.

The log distribution for the simulated logs is shown in Figure B2. Log size class variation in sawmills can vary depending on supply constraints but results from this study can be weighted if required for application to a sawmill with a different log intake distribution.

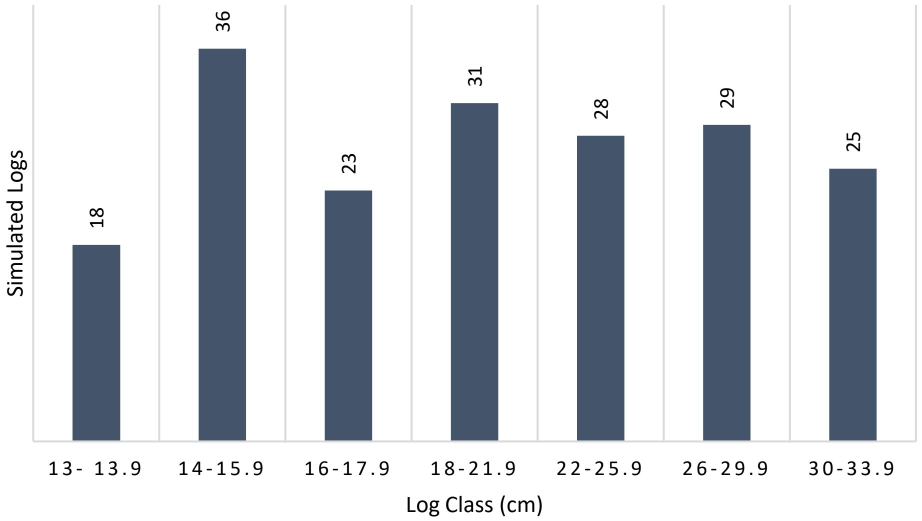


Figure B2: Distribution of simulated logs, per log class

Log Class Definitions

Log Class No.	Diameter (cm)		Length (m)			Taper (mm/m)		Sweep (mm/m		Ovality		Defect Core (%)	
	Min	Max	Min	Max	Incr	Min	Max	Min	Max	Min	Max	Min	Max
1	13.0	13.9	1.8	6.6	0.3	0.0	25.0	0.0	40.0	0.50	1.50	0	100
2	14.0	15.9	1.8	6.6	0.3	0.0	25.0	0.0	40.0	0.50	1.50	0	100
3	16.0	17.9	1.8	6.6	0.3	0.0	25.0	0.0	40.0	0.50	1.50	0	100
4	18.0	21.9	1.8	6.6	0.3	0.0	25.0	0.0	40.0	0.50	1.50	0	100
5	22.0	25.9	1.8	6.6	0.3	0.0	25.0	0.0	40.0	0.50	1.50	0	100
6	26.0	29.9	1.8	6.6	0.3	0.0	25.0	0.0	40.0	0.50	1.50	0	100
7	30.0	33.9	1.8	6.6	0.3	0.0	25.0	0.0	40.0	0.50	1.50	0	100

Figure B2: The log sorting classes of the simulated sawmill

A range for the minimum and maximum values for log properties namely, taper, sweep and ovality, were defined as detailed in Figure 19. Real world range of specifications for the log properties were used.

1 Log data source

Logs were generated in Simsaw 6 using the log generator function. To guarantee the repeatability of the log generation, a random seed of 1 was used in Simsaw 6. This ensured that the exact same log models were used across the simulations within each of the four simulation schemes.

The percentage variation field was then populated as shown in Table. It allows the user to specify the variation of parameters that should be assumed in the generation of the log cross sections. Logs were generated with 10 cross sections and 32 points per disc. The cross sections generated would then be supplemented by interpolated data during the running of simulations.

Table B1: Percentage variation in designated properties of the generated logs

Diameter (%)	Taper (%)	Sweep (%)	Ovality (%)
2	2	10	2

The ranges of the log characteristics populated in the log generator to simulate the desired logs are shown in Table. Taper, sweep and ovality were normally distributed 95 within limits whilst the dimeter and length were uniformly distributed.

Table B2: Log properties of the simulated logs

Diameter (cm)	Length (m)	Taper (mm/m)	Sweep (mm/m)	Ovality
13 - 33. 9+	3. 0 -4. 8m	8. 0 - 12. 0	0. 0-15. 0	0. 95 - 1. 05

3 Product definitions

The thickness, width, and length of both the dry and wet nominal dimensions of the boards were specified. The standard sawing pattern (SSP) dimensions currently adopted by most sawmill in South Africa, as per SANS 1783-1, are detailed in
Figure. Throughout this research, this will be referred to as the standard sawing pattern (SSP). The grade option from the simulation software was not activated in this study.

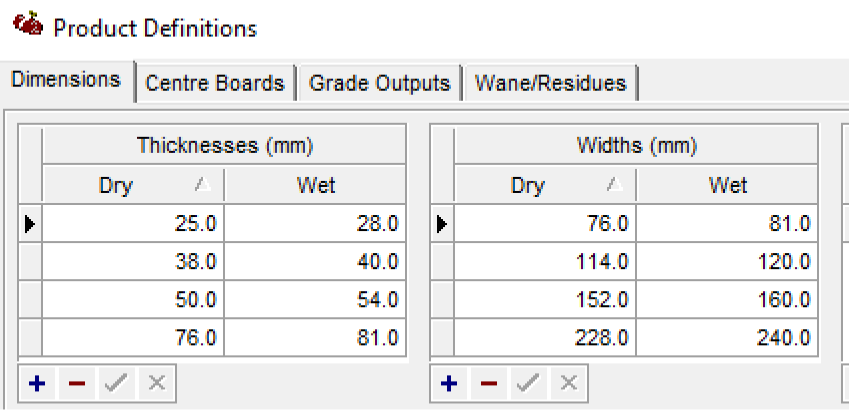
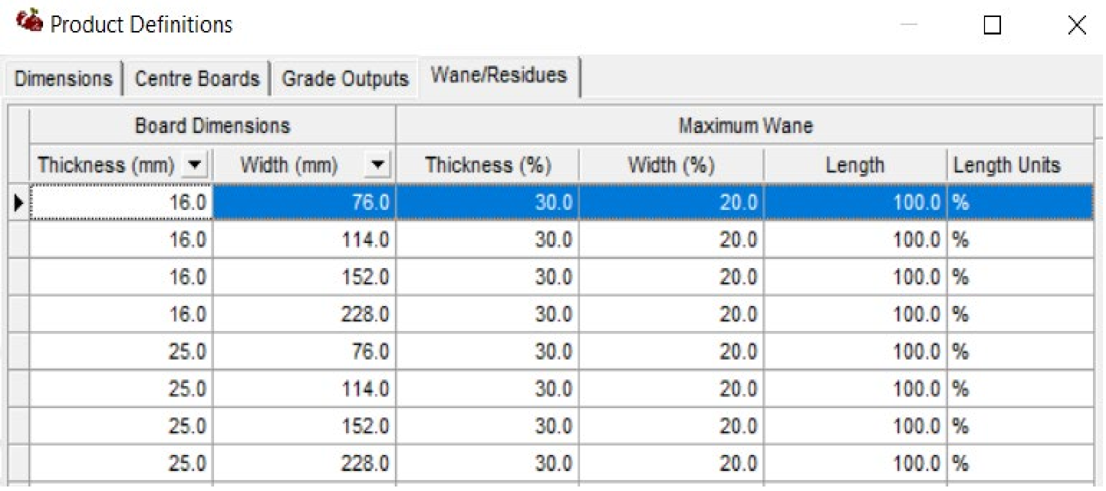


Figure B3: Standard board dimensions used in the standard sawing pattern

4 Wane and residues

The tab from Simsaw 6, shown in
Figure B4 enables users to define the percentage wane specifications. The SSP wane specifications thickness, width, and length can be seen in
Figure B4. These were then changed for the other simulation schemes.


Product Definitions

Dimensions | Centre Boards | Grade Outputs | Wane/Residues

Board Dimensions		Maximum Wane			
Thickness (mm)	Width (mm)	Thickness (%)	Width (%)	Length	Length Units
16.0	76.0	30.0	20.0	100.0	%
16.0	114.0	30.0	20.0	100.0	%
16.0	152.0	30.0	20.0	100.0	%
16.0	228.0	30.0	20.0	100.0	%
25.0	76.0	30.0	20.0	100.0	%
25.0	114.0	30.0	20.0	100.0	%
25.0	152.0	30.0	20.0	100.0	%
25.0	228.0	30.0	20.0	100.0	%

Figure B4: Board dimensions and allowed wane specifications

5 Machine Settings

The simulated sawmill utilized a double band sawing machine. For all the four simulation themes, the cant sawing method was used. The machine settings options included Primary Breakdown, Secondary Breakdown and Edging/ X-cut/ Resaw as shown in ***Figure***.

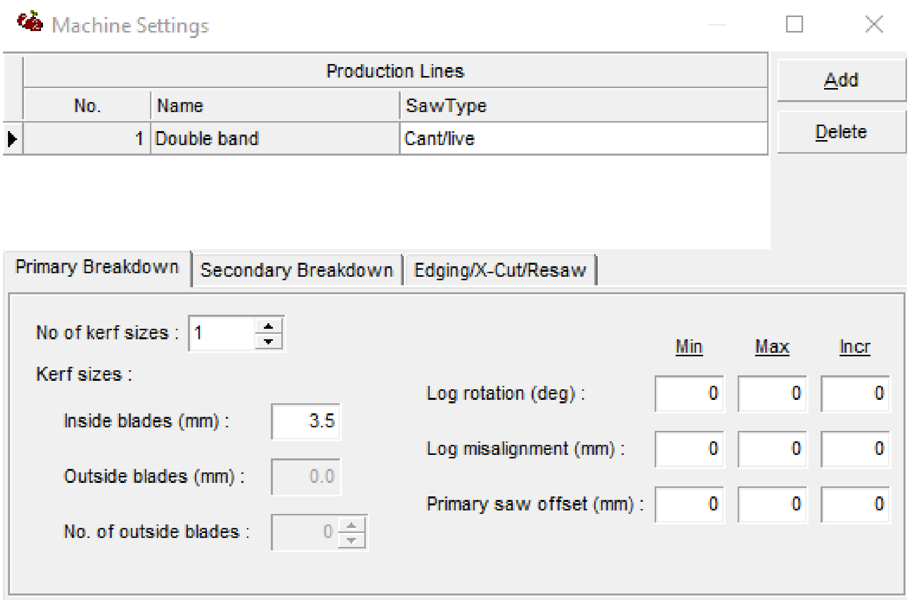


Figure B5: Sawmill machine settings in Simsaw 6 simulation software.

Primary breakdown

Only one kerf size was used, with inside blades of 3. 5 mm. The logs were thought to be fed through the primary breakdown in a “horns- up” position. No log rotation options were applied. The cant misalignment option was also not used, since it was assumed that logs were not skewed during feeding onto the saw.

<u>Secondary Breakdown Settings</u>

One kerf size was used, with an inside blade of 4mm. Half taper option was selected to guide the secondary saw around the curve. The cant is assumed to be fed straight through the secondary breakdown saw hence no cant misalignment was used. No offsetting was simulated hence the secondary saw offset option was not used either.

<u>Edging/ Cross -cut/ Resaw</u>

This process aimed to saw for maximum volume. Two edging blades were used with a kerf size of 5mm.

6 Sawing patterns

Lastly, the sawing patterns for each log class were defined. A typical sawing pattern interface in Simsaw 6 is depicted in
Figure.

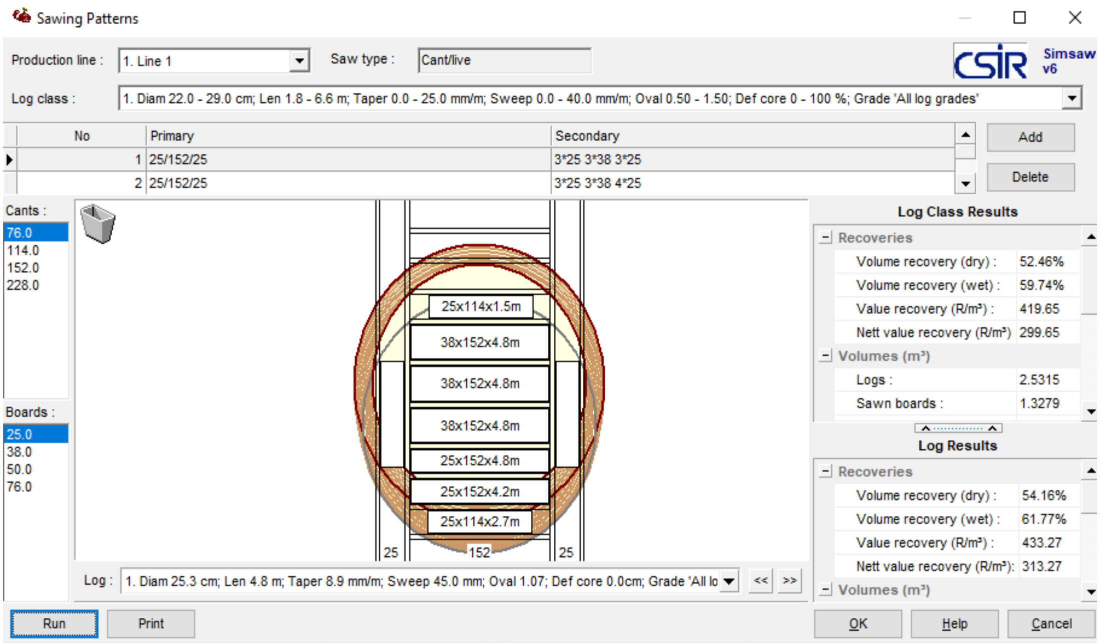


Figure B6: Shows the user interface of Saw2003.

7 Base Case
The Simsaw inputs below were used for simulating the SSP scenarios.

Log Class Definitions

Log (	Diameter (c		Length (m)			Taper (mm		Sweep (mn		Ovality		Defect Cor		Grades	Price (	No. of
	Min	Max	Min	Max	Incr	Min	Max	Min	Max	Min	Max	Min	Max			
1	13.0	13.9	1.8	3.0	0.3	0.0	25.0	0.0	40.0	0.50	1.50	0	100		120.0(	18
2	14.0	15.9	1.8	3.0	0.3	0.0	25.0	0.0	40.0	0.50	1.50	0	100		120.0(	36
3	16.0	17.9	1.8	3.0	0.3	0.0	25.0	0.0	40.0	0.50	1.50	0	100		120.0(	23
4	18.0	21.9	1.8	3.0	0.3	0.0	25.0	0.0	40.0	0.50	1.50	0	100		120.0(	31
5	22.0	25.9	1.8	3.0	0.3	0.0	25.0	0.0	40.0	0.50	1.50	0	100		120.0(	28
6	26.0	29.9	1.8	3.0	0.3	0.0	25.0	0.0	40.0	0.50	1.50	0	100		120.0(	29
7	30.0	33.9	1.8	3.0	0.3	0.0	25.0	0.0	40.0	0.50	1.50	0	100		120.0(	25

Figure B7: SSP -log definitions

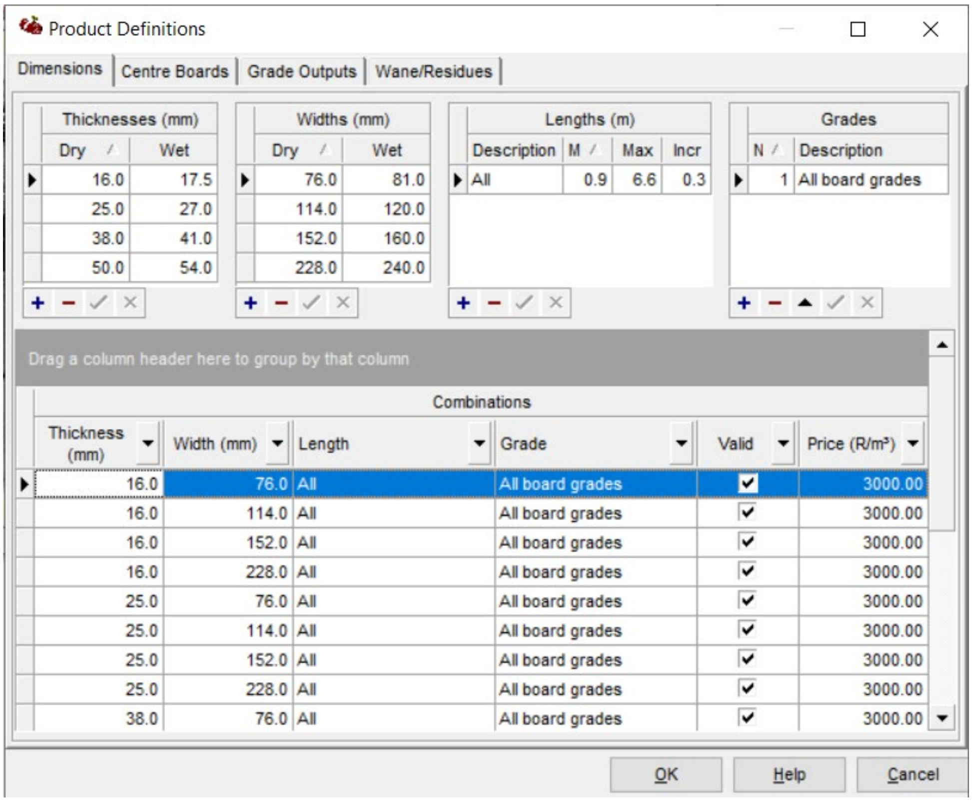


Figure B8: SSP -Log definitions

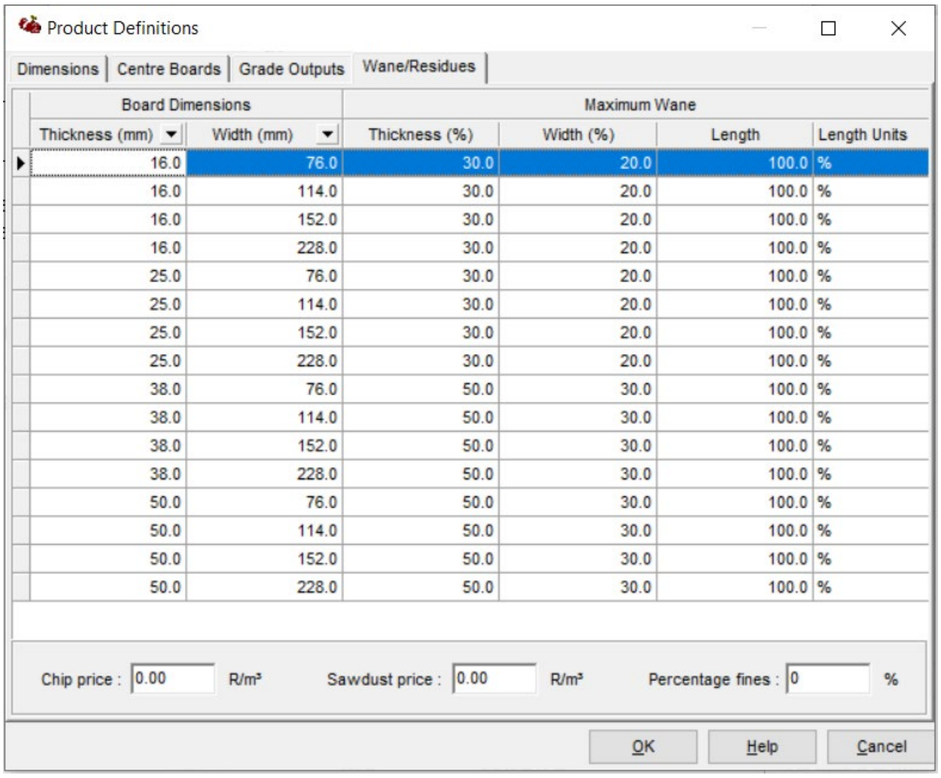


Figure B9: SSP- Wane rules, product definitions

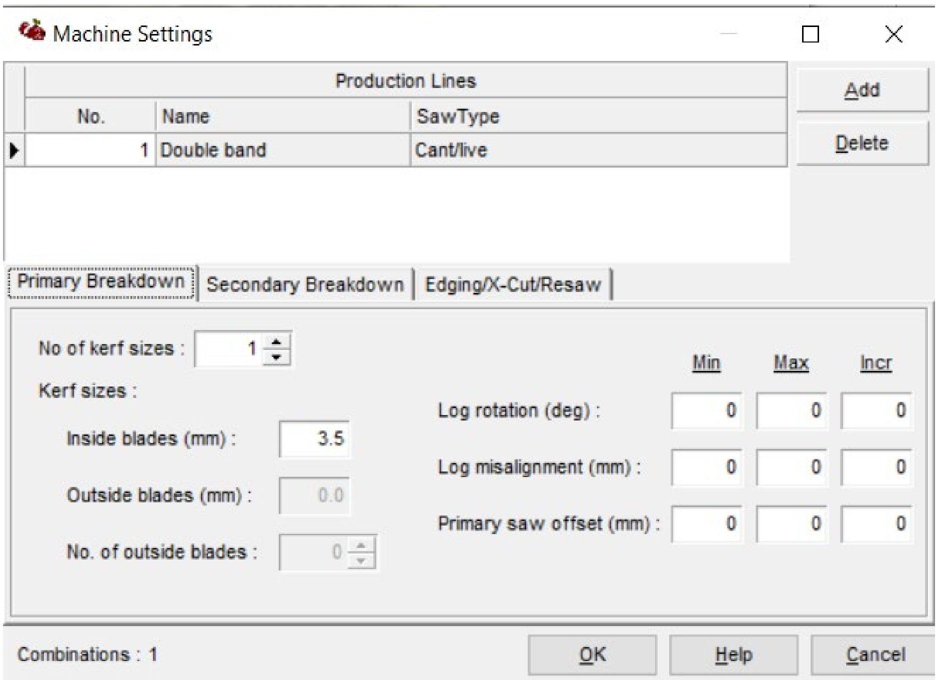


Figure B10: SSP- Machine settings inputs, primary log breakdown

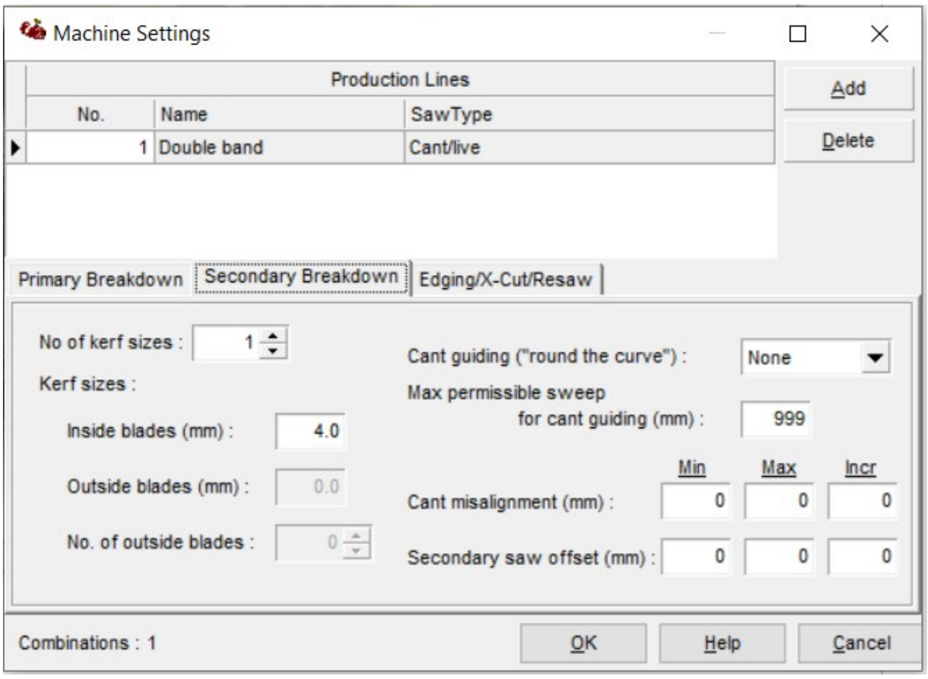


Figure B11: SSP- Machine settings inputs, secondary breakdown

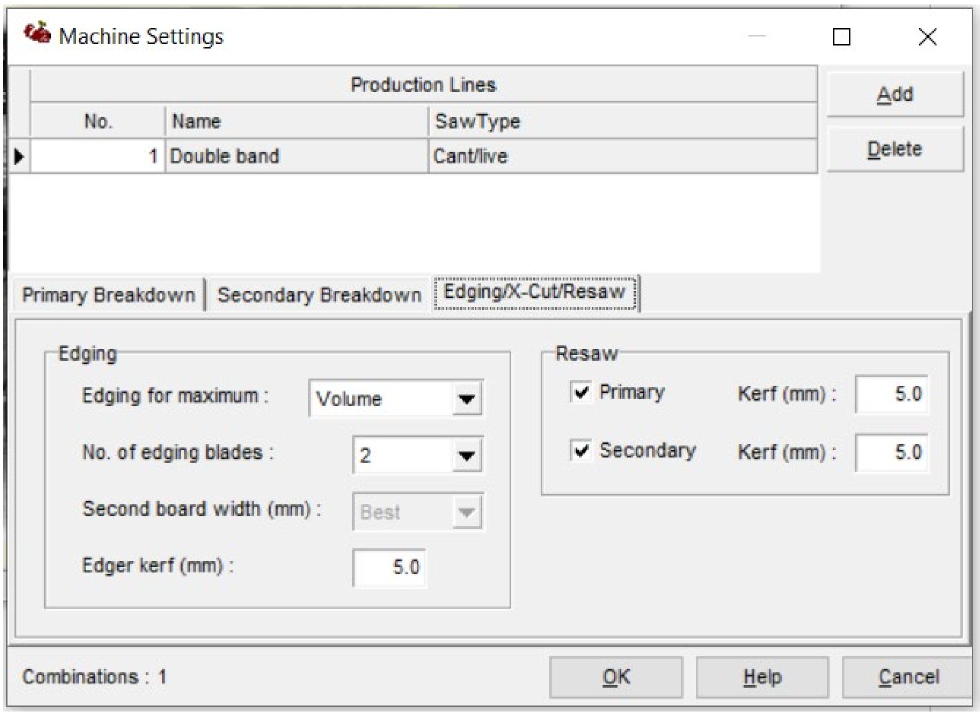


Figure B12: SSP- Machine settings inputs, Edging/X-cut/resaw

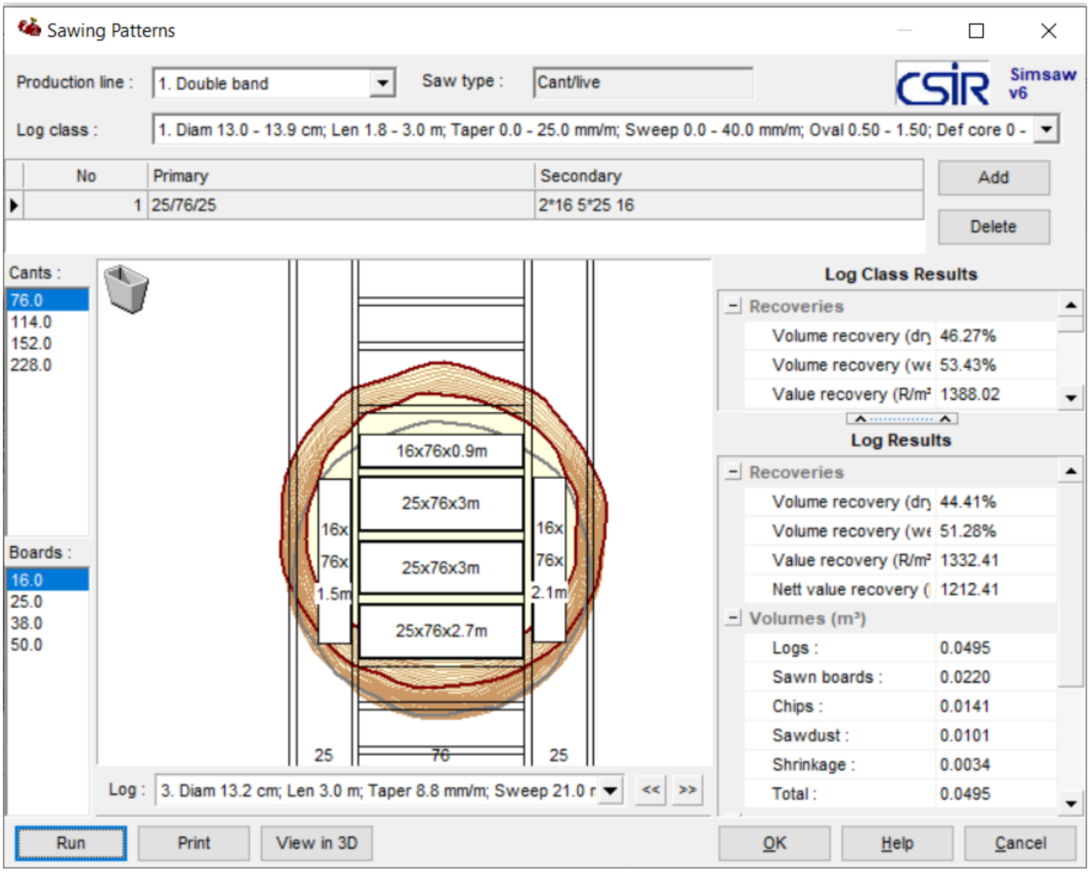
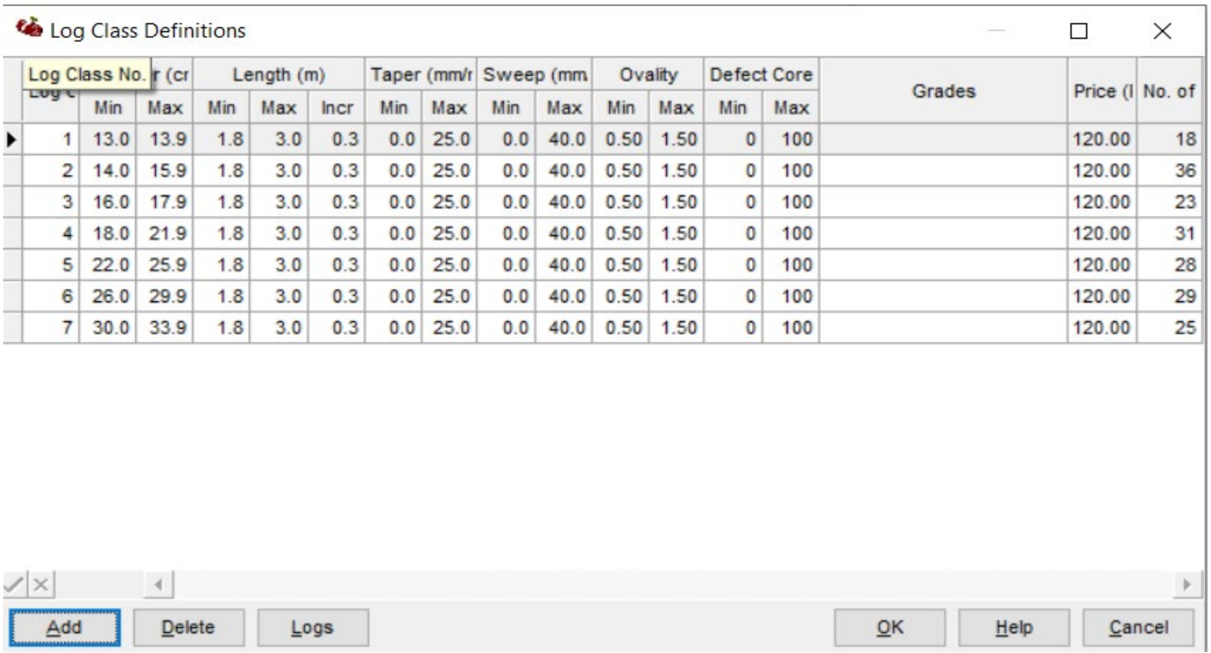


Figure B13: SSP- Sawing patterns

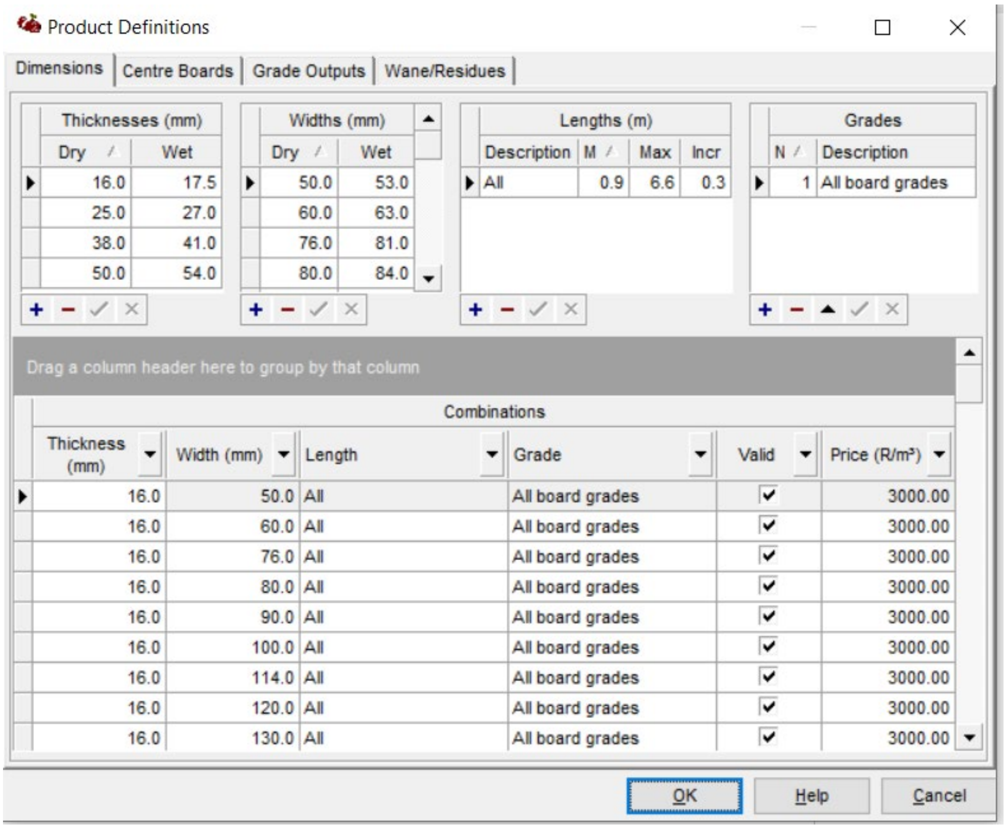
8 Random widths (RW)

The RW scenarios use the same inputs as the SSP, however the product definitions will differ. The input product details are detailed in the figures that follow.



Log Class No.	r (cr		Length (m)			Taper (mm/r		Sweep (mm		Ovality		Defect Core		Grades	Price (I	No. of
	Min	Max	Min	Max	Incr	Min	Max	Min	Max	Min	Max	Min	Max			
1	13.0	13.9	1.8	3.0	0.3	0.0	25.0	0.0	40.0	0.50	1.50	0	100		120.00	18
2	14.0	15.9	1.8	3.0	0.3	0.0	25.0	0.0	40.0	0.50	1.50	0	100		120.00	36
3	16.0	17.9	1.8	3.0	0.3	0.0	25.0	0.0	40.0	0.50	1.50	0	100		120.00	23
4	18.0	21.9	1.8	3.0	0.3	0.0	25.0	0.0	40.0	0.50	1.50	0	100		120.00	31
5	22.0	25.9	1.8	3.0	0.3	0.0	25.0	0.0	40.0	0.50	1.50	0	100		120.00	28
6	26.0	29.9	1.8	3.0	0.3	0.0	25.0	0.0	40.0	0.50	1.50	0	100		120.00	29
7	30.0	33.9	1.8	3.0	0.3	0.0	25.0	0.0	40.0	0.50	1.50	0	100		120.00	25

Figure B14: RW- log definitions, the same as SSP and IW and IW+RW



Thicknesses (mm)	
Dry	Wet
16.0	17.5
25.0	27.0
38.0	41.0
50.0	54.0

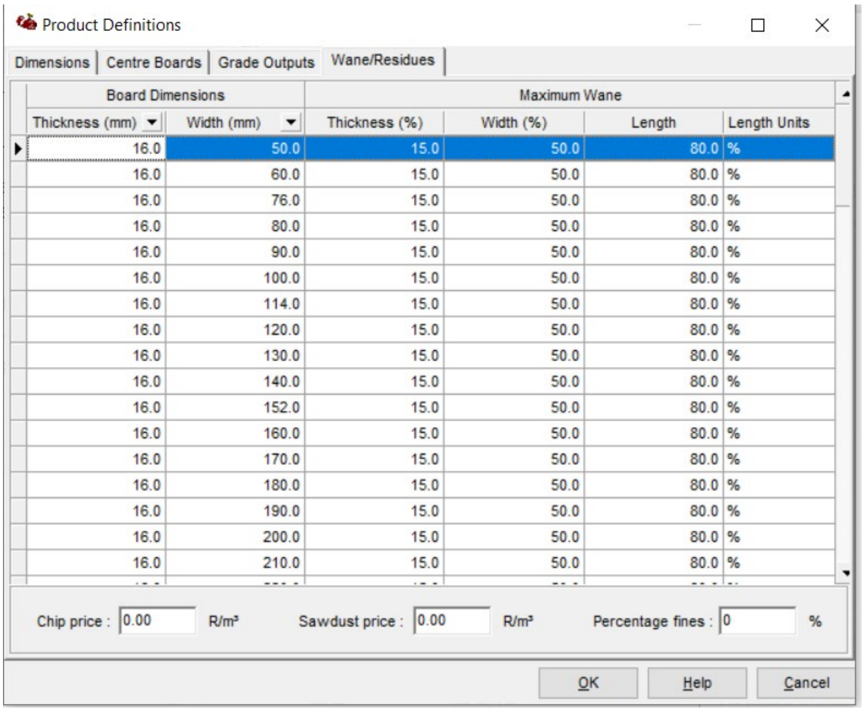
Widths (mm)	
Dry	Wet
50.0	53.0
60.0	63.0
76.0	81.0
80.0	84.0

Lengths (m)			
Description	M	Max	Incr
All	0.9	6.6	0.3

Grades	
N	Description
1	All board grades

Combinations					
Thickness (mm)	Width (mm)	Length	Grade	Valid	Price (R/m³)
16.0	50.0	All	All board grades	✓	3000.00
16.0	60.0	All	All board grades	✓	3000.00
16.0	76.0	All	All board grades	✓	3000.00
16.0	80.0	All	All board grades	✓	3000.00
16.0	90.0	All	All board grades	✓	3000.00
16.0	100.0	All	All board grades	✓	3000.00
16.0	114.0	All	All board grades	✓	3000.00
16.0	120.0	All	All board grades	✓	3000.00
16.0	130.0	All	All board grades	✓	3000.00

Figure B15: RW -product definitions



Board Dimensions		Maximum Wane			
Thickness (mm)	Width (mm)	Thickness (%)	Width (%)	Length	Length Units
16.0	50.0	15.0	50.0	80.0	%
16.0	60.0	15.0	50.0	80.0	%
16.0	76.0	15.0	50.0	80.0	%
16.0	80.0	15.0	50.0	80.0	%
16.0	90.0	15.0	50.0	80.0	%
16.0	100.0	15.0	50.0	80.0	%
16.0	114.0	15.0	50.0	80.0	%
16.0	120.0	15.0	50.0	80.0	%
16.0	130.0	15.0	50.0	80.0	%
16.0	140.0	15.0	50.0	80.0	%
16.0	152.0	15.0	50.0	80.0	%
16.0	160.0	15.0	50.0	80.0	%
16.0	170.0	15.0	50.0	80.0	%
16.0	180.0	15.0	50.0	80.0	%
16.0	190.0	15.0	50.0	80.0	%
16.0	200.0	15.0	50.0	80.0	%
16.0	210.0	15.0	50.0	80.0	%

Figure B16: RW – Wane specifications

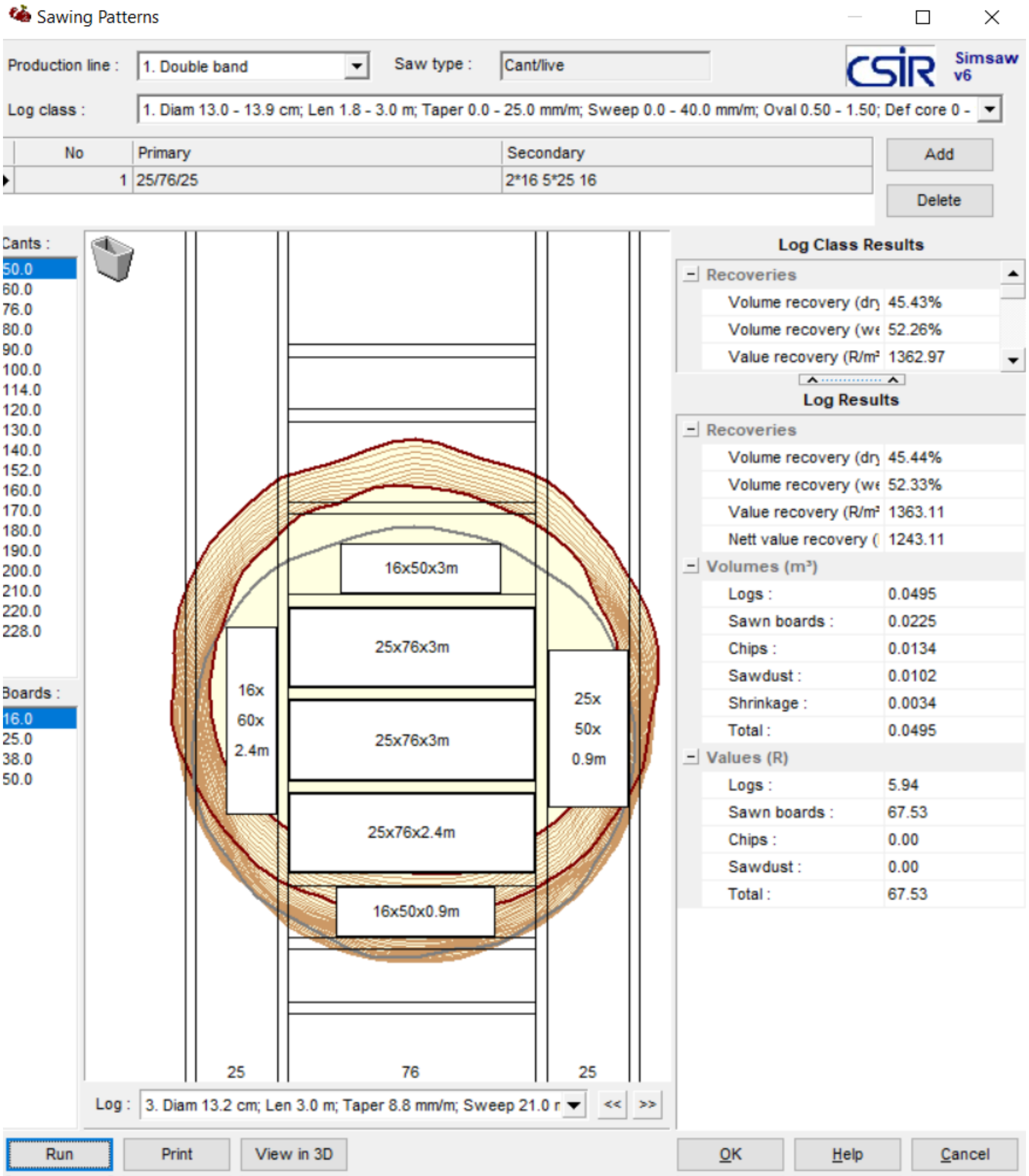
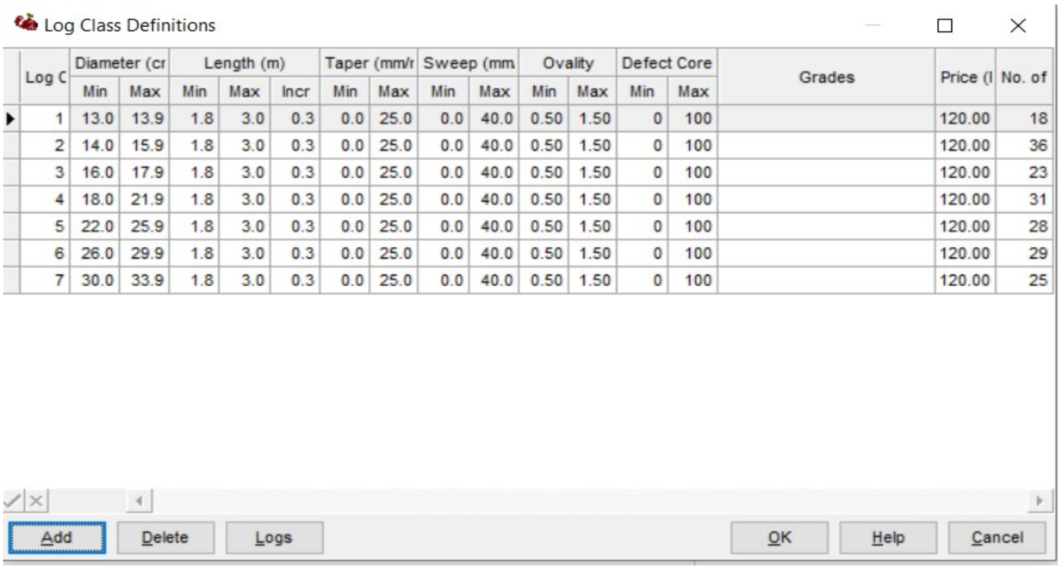


Figure B17: RW-sawing patterns

9 RW+IW

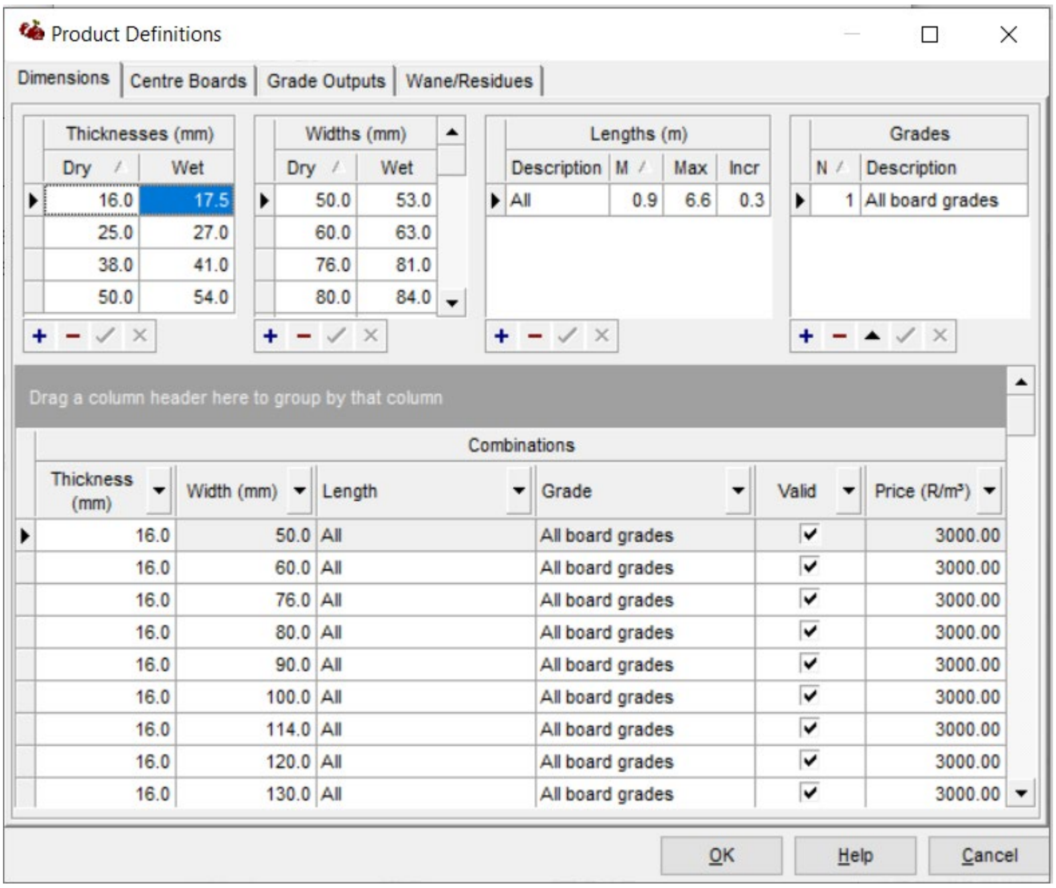
The RW+IW scenarios also used the same inputs as the SSP; however, the product definitions will differ. The input product details are detailed in the figures that follow.



Log Class Definitions

Log C	Diameter (cr		Length (m)			Taper (mm/r		Sweep (mm		Ovality		Defect Core		Grades	Price (I	No. of
	Min	Max	Min	Max	Incr	Min	Max	Min	Max	Min	Max	Min	Max			
1	13.0	13.9	1.8	3.0	0.3	0.0	25.0	0.0	40.0	0.50	1.50	0	100		120.00	18
2	14.0	15.9	1.8	3.0	0.3	0.0	25.0	0.0	40.0	0.50	1.50	0	100		120.00	36
3	16.0	17.9	1.8	3.0	0.3	0.0	25.0	0.0	40.0	0.50	1.50	0	100		120.00	23
4	18.0	21.9	1.8	3.0	0.3	0.0	25.0	0.0	40.0	0.50	1.50	0	100		120.00	31
5	22.0	25.9	1.8	3.0	0.3	0.0	25.0	0.0	40.0	0.50	1.50	0	100		120.00	28
6	26.0	29.9	1.8	3.0	0.3	0.0	25.0	0.0	40.0	0.50	1.50	0	100		120.00	29
7	30.0	33.9	1.8	3.0	0.3	0.0	25.0	0.0	40.0	0.50	1.50	0	100		120.00	25

Figure B18: RW +IW - log definitions, the same as SSP and IW and IW+RW



Product Definitions

Dimensions | Centre Boards | Grade Outputs | Wane/Residues

Thicknesses (mm)	
Dry	Wet
16.0	17.5
25.0	27.0
38.0	41.0
50.0	54.0

Widths (mm)	
Dry	Wet
50.0	53.0
60.0	63.0
76.0	81.0
80.0	84.0

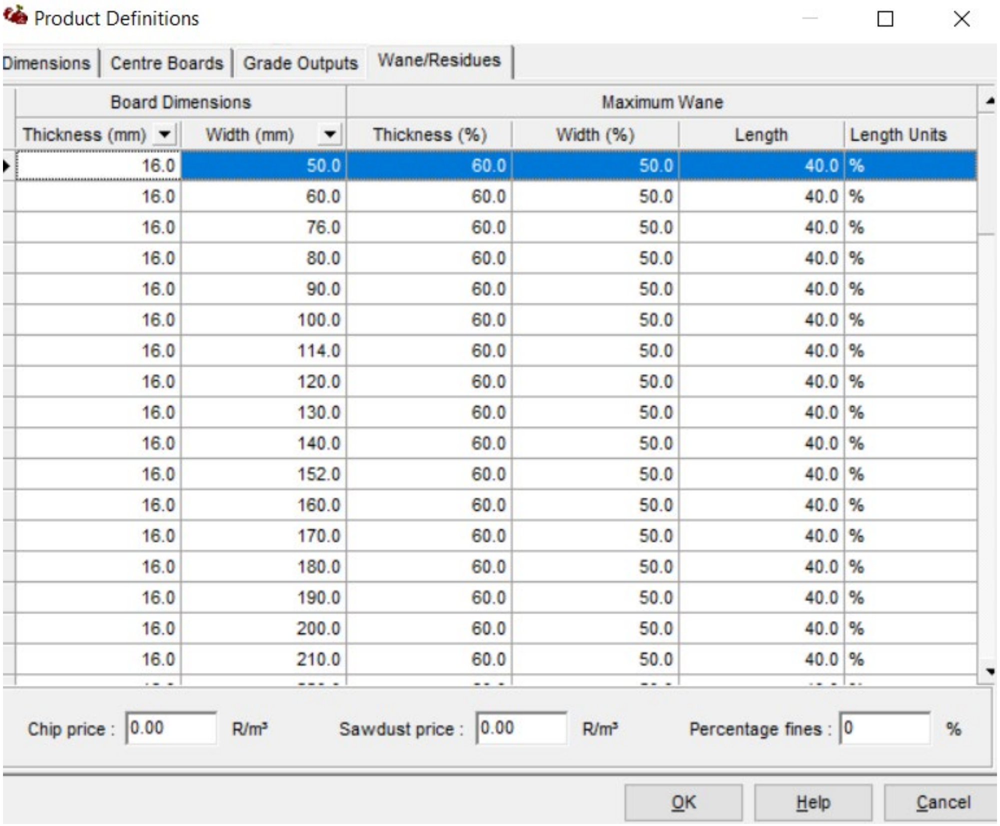
Lengths (m)			
Description	M	Max	Incr
All	0.9	6.6	0.3

Grades	
N	Description
1	All board grades

Combinations

Thickness (mm)	Width (mm)	Length	Grade	Valid	Price (R/m³)
16.0	50.0	All	All board grades	✓	3000.00
16.0	60.0	All	All board grades	✓	3000.00
16.0	76.0	All	All board grades	✓	3000.00
16.0	80.0	All	All board grades	✓	3000.00
16.0	90.0	All	All board grades	✓	3000.00
16.0	100.0	All	All board grades	✓	3000.00
16.0	114.0	All	All board grades	✓	3000.00
16.0	120.0	All	All board grades	✓	3000.00
16.0	130.0	All	All board grades	✓	3000.00

Figure B19: RW +IW - Product definitions



Board Dimensions		Maximum Wane			
Thickness (mm)	Width (mm)	Thickness (%)	Width (%)	Length	Length Units
16.0	50.0	60.0	50.0	40.0	%
16.0	60.0	60.0	50.0	40.0	%
16.0	76.0	60.0	50.0	40.0	%
16.0	80.0	60.0	50.0	40.0	%
16.0	90.0	60.0	50.0	40.0	%
16.0	100.0	60.0	50.0	40.0	%
16.0	114.0	60.0	50.0	40.0	%
16.0	120.0	60.0	50.0	40.0	%
16.0	130.0	60.0	50.0	40.0	%
16.0	140.0	60.0	50.0	40.0	%
16.0	152.0	60.0	50.0	40.0	%
16.0	160.0	60.0	50.0	40.0	%
16.0	170.0	60.0	50.0	40.0	%
16.0	180.0	60.0	50.0	40.0	%
16.0	190.0	60.0	50.0	40.0	%
16.0	200.0	60.0	50.0	40.0	%
16.0	210.0	60.0	50.0	40.0	%

Figure B20: RW +IW– Wane specifications

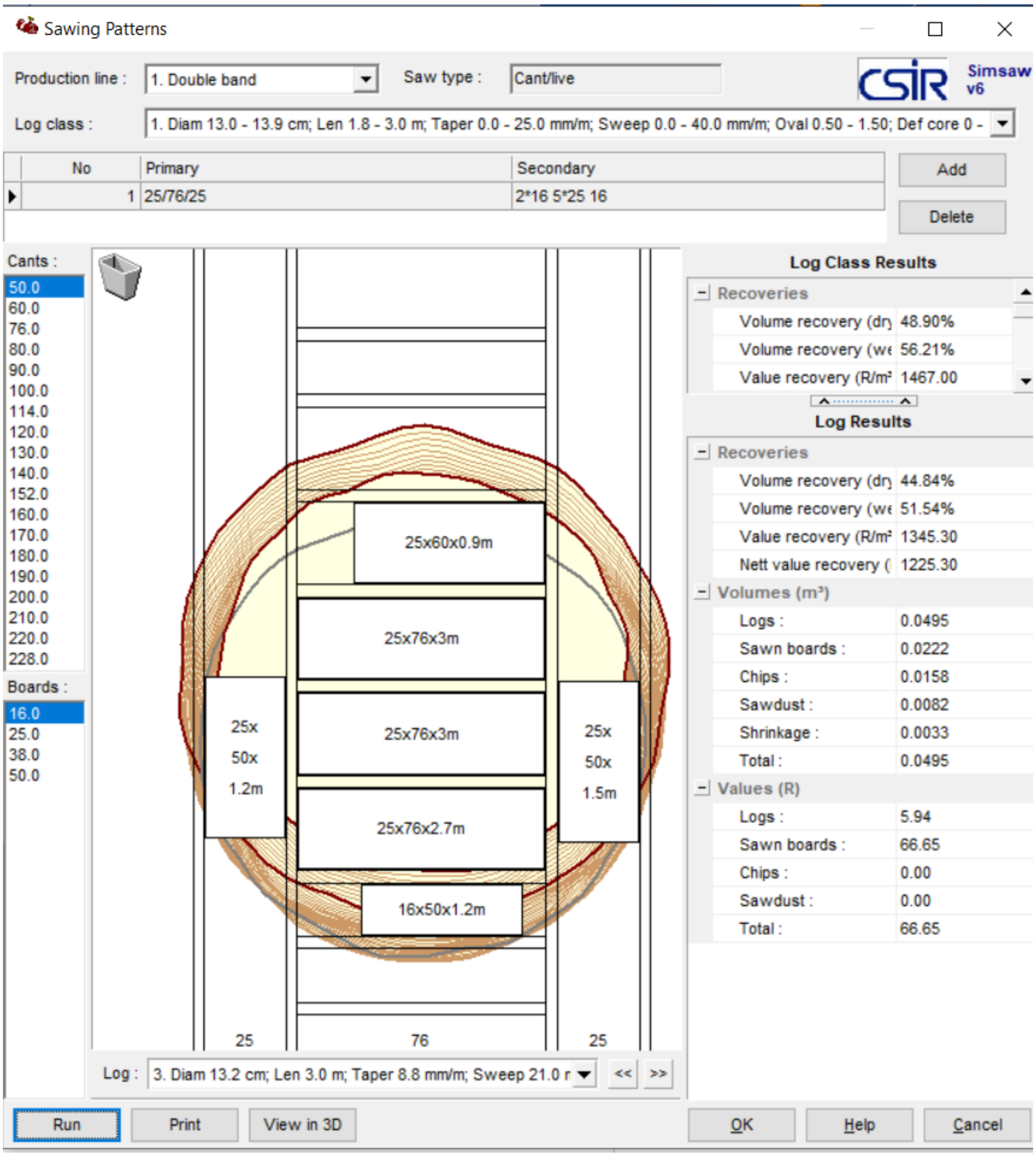


Figure B21: IRW+IW Sawing patterns

Appendix C

The board failure modes of the CLT panels are depicted in this appendix. It is worth noting that the boards failed in areas with bigger knots, and no delammination occurred because of wane.

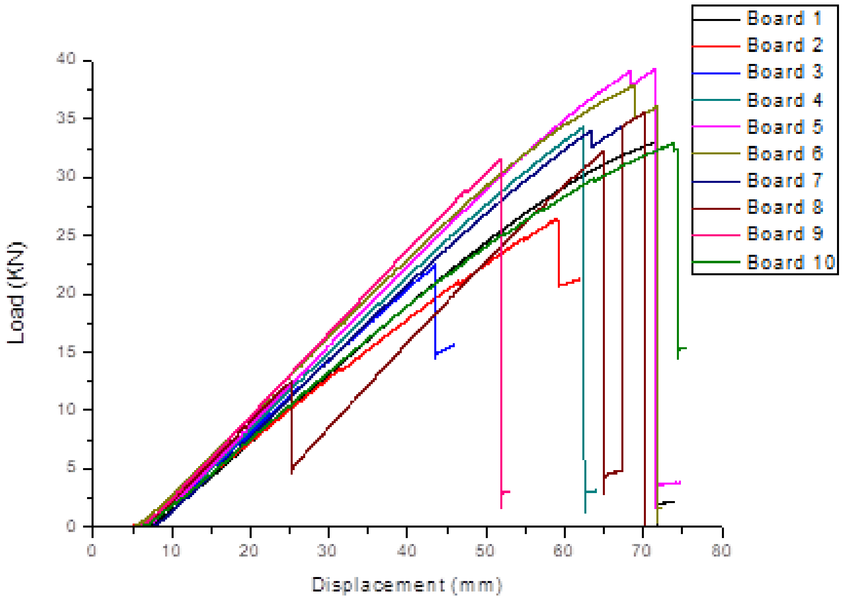


Figure C1: Load deflection curve for the ten CLT panels

Table C1: Failure modes in CLT panels

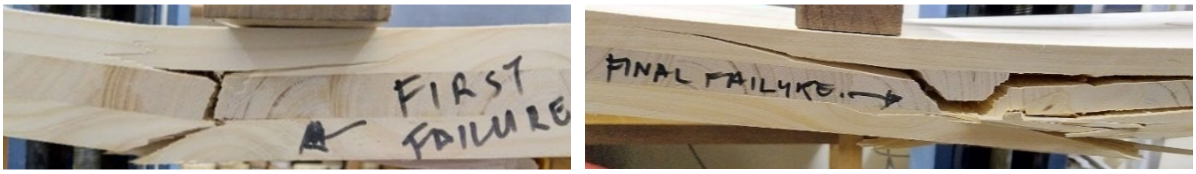
CLT Panel 10

CLT Panel 9

CLT Panel 8

CLT Panel 7

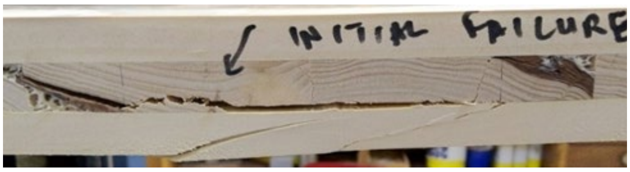
CLT Panel 5



CLT Panel 4

Table C2: Failure modes in CLT panels during destructive tests

CLT panel 4



CLT panel 3

CLT panel 2

CLT panel 1

Appendix D

Knot distribution on the CLT boards: The effect of knot characteristics on the CLT strength properties

Table D1: Failure modes in the bottom CLT lamella, showing knot orientation

Panel 1

Panel 2

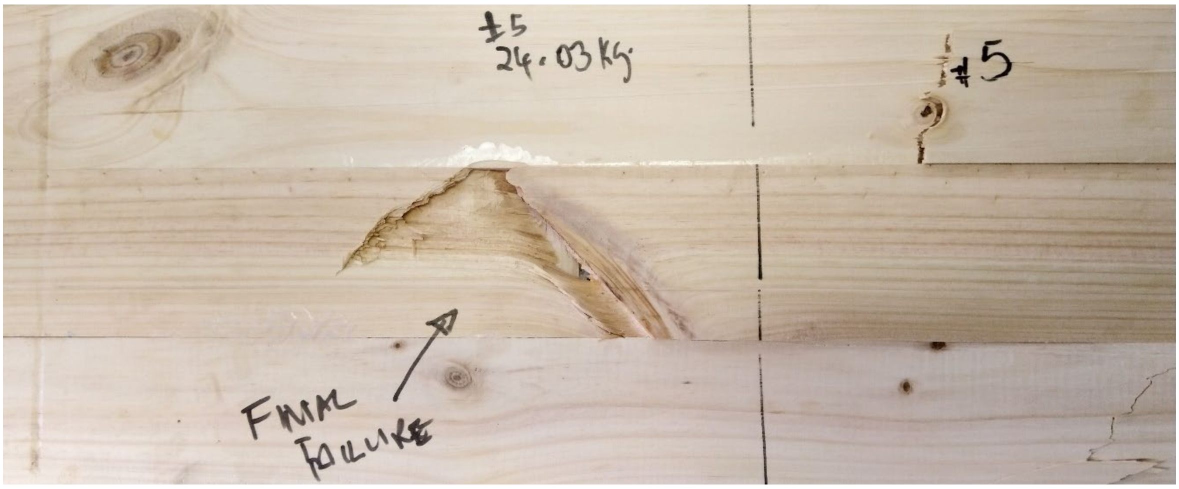
Panel 3

Panel 4

Table D2: Failure modes in the bottom CLT lamella, showing knot orientation

Panel 5. 1

Panel 5. 2



Panel 6

Panel 7

Table D3: Failure modes in the bottom CLT lamella, showing knot orientation

Panel 8

Panel 9

Panel 10