OPTIMIZATION OF ON-FARM MACHINE DESIGN PARAMETERS FOR ECO-EFFICIENT TIMBER SAWING BASED ON EMPIRICAL APPROACH

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Optimization of On-Farm Machine Design Parameters for Eco-Efficient Timber Sawing Based On Empirical Approach

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DECLARATION

This thesis is my original work and has not been presented for a degree in any other University.

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This thesis has been submitted for examination with our approval as the university supervisors.

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DEDICATION

This work is dedicated to my late parents Benard and Itumbi Muthike, who, though not educated, saw the importance of education and took me to school under difficult circumstances. They encouraged me to keep learning despite the challenges of youth until schooling discipline was sunk in my mind. They sacrificed all for my schooling and applied optimum discipline to achieve the same.

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LIST OF ABBREVIATIONS AND ACRONYMS

AEV	Annual Equivalent Value
CO	Carbon monoxide
EAV	Exposure action value
ELV	Exposure limit value
EMC	Equilibrium moisture content
EUPA	European Union Physical Agents
HAV	Hand arm vibration
ISO	International Standards Organization
IRR	Internal rate of return
KEFRI	Kenya Forestry Research Institute
KFS	Kenya Forestry Service
LT	Traverse limit
MSD	Musculoskeletal disorders
NIOSH	National Institute for Occupational Safety and Health
NPV	Net Present Value
OCRA	Occupational Repetitive Action
OWAS	Ovako Working-posture Analysis System
RH	Relative humidity

SPSS	Statistical package for social scientists
VL	Vertical limit
WBV	Whole body vibration

ABSTRACT

This study compared performance of three timber sawing systems; chain, bench and pit saws determined the optimal design parameters of the chainsaw system using polynomial functions. Results showed significant differences among the sawing systems at p=0.05. Chainsaw system recorded higher timber production rate of 0.23m^3/man-hour than 0.17and 0.08m^3/man-hour for bench and pit saws, respectively. However, chainsaw's recovery rate was significantly lower at 30% compared to 39.8% and 35.9% for pit and bench saws respectively. Timber sawn with chain saw had significantly higher dimensional variability (±5.53mm), than that sawn with pit and bench saws at ±2.64mm and ±3.55mm respectively. Application of empirical approach successfully determined the optimal chainsaw design parameters as3.02m/min for sawing speed, 6.87lt/m^3 for fuel consumption and ±1.25mm for dimensional variability. These values were obtainable at a cutter angle of about 25^o and depth gauge clearance of 0.650mm. The optimized chain, attached to a framed chainsaw, recorded timber recovery of 52.3% which was significantly higher than that for freehand chainsaw (30.2%).The optimized system achieved lower dimensional variability and surface roughness of when compared with the freehand chainsaw system. The system reduced the operator exposure to vibration and noise, and also lead to reduced solid wastes released to the environment. The framed chainsaw system is therefore recommended as appropriate for timber sawyers operating on the farms, where trees are few, scattered and small in diameter.

CHAPTER ONE

INTRODUCTION

1.1 Background to the Study

Agro-forestry sub-sector contributes substantially to the growth of national economies of different countries in the world (Wamahiu, 2008). With natural forests being increasingly protected for the 'global good' and forest plantations having to compete with agriculture for limited space in state or communal land, trees growing for timber on farms continue to be an important supplement (Pasiecznik, 2000; World Agroforestry Centre, 2004). Farm forestry therefore has a huge potential to meet the demand for more wood, if the vast dry lands can also be turned into productive agro-forests. This can be achieved through matching them with the right species and farmers being empowered with appropriate skills and technologies (Felker, 2000; Pasiecznik, 2000). However, outside traditional forest zones like dry lands and farms, wood from unprocessed trees provides relatively little income when sold for fuel, posts or unprocessed logs. In some areas, studies on the sawn wood value chain indicated that tree owners get as little as 10% of the sawn timber value when they sell the standing trees (Muhumuza *et al.*, 2007). Felling and transporting scattered trees to the nearest sawmill has also been shown to be uneconomical (Muthike *et al.*, 2010; Marfo, 2010). Sawing logs on-site increases value and revenues to the tree owners, encouraging the farmer to plant more. This improves local economies by providing raw materials for local construction needs and employment for the local saw operators (Samuel *et al.*, 2007).

Timber sawing, especially from plantation forests plays a major role in development. In Kenya, sawmilling provides employment to many people in forested rural areas before the Government moratorium on tree harvesting from state forests in 1999 (Muthike *et al.*, 2008). This ban reduced wood supplies to most wood based industries, culminating in closure of most of the saw mills in the country. As a result, socioeconomic development was adversely affected due to reduced employment opportunities especially in areas where the local economy depended on the industry (Muthike *et al*., 2010). It also resulted in an acute shortage of timber products, prompting increase in sawn timber imports from neighbouring countries. Consequently, cross-border timber trade, both legal and illegal emanated, making timber trade in Kenya a major challenge (Samuel *et al.*, 2007). In an effort to sustain their operations, a few saw millers turned to farms as supplemental source of logs. This however became uneconomical due to increased distances to the tree source. Local sawyers using small-scale sawing systems took up the operations on farms to provide the highly needed sawn timber (Holding *et al*., 2001; Holding-Anyonge & Roshetko, 2003).

Three types of equipment and sawing techniques, which include movable bench saws, chain and pit saws are used (Pasiecznik, 2010; Muthike *et al*., 2010). Bench saw machines were used mainly in areas where raw materials were available in relatively large quantities and easily accessible by a tractor. Pit saws are used in very remote areas, especially where trees grow in steep terrains limiting to the bench saws. Chainsaws, although not initially designed for processing dimensional timber, have been adopted because they generally require relatively low initial investment. They have been used in areas that are not easily accessible by conventional saw milling or the movable bench saw equipment (Pasiecznik and Brewer, 2006; Marfo, 2010). They involve less invasive equipment than conventional saw milling, manual labour is used instead of skidders, and small hand-held machines instead of large heavy duty fixed mills (Wit *et al*., 2010). Because of these advantages, chainsaws have been constantly replacing the other systems and have become the dominant sawing system on farms (Muthike *et al*., 2008).

Over the years, chainsaw system has become widespread as means for producing timber in small volumes from isolated trees and trees in difficult terrain as well as deformed logs. It has become a major source of livelihood for small operators, farmers and the rural communities in various developing countries (Wit *et al*., 2010; Pasiecznik, 2010). In Kenya, chainsaws are responsible for sawing of significant amounts of timber, both inside and outside forests, legally and illegally (Muthike *et al*., 2010; Samuel *et al*., 2007). The possibility of making a reasonable living from on-farm timber sawing and the scarcity or lack of other viable livelihood alternatives in many rural areas are cited as powerful drivers for people to get involved in the practice (Marfo, 2010). Although employment figures for on-farm timber sawing are not readily available since in most countries it is practiced in an informal setup, its employment potential is estimated to form a substantial part of the total forestry workforce for some countries (Wit *et al*., 2010). It forms a major window of employment, providing jobs to an estimated 97,000 people in Ghana (Marfo & Acheampong, 2011) and 45,000 in Cameroon (Marfo & Acheampong, 2009).

Conversion efficiencies of sawing systems are very important in sustainable production of sawn timber in a contemporary world (Pasiecznik, 2010). Timber sawing efficiency is influenced by among others; sawing systems, machine design characteristics in the and their modes of operation (Muthike, 2004). Machine design characteristics are related to the cutting tools, the size of their kerfs, the way they are arranged on the sawing machine and their stability during the sawing process. Modes of operation are important in determining not only efficiency but also the ergonomic characteristics and the risks associated with the operation of the sawing equipment (Occhipinti, 1998).

1.2 Statement of the Problem

Numerous studies have documented inefficiency in on-farm timber sawing systems, in regard to particularly timber recovery (Owusu *et al.*, 2011; Marfo, 2010; Muthike *et al.*, 2008; Samuel *et al.*, 2007; Pasieznick *et al.*, 2006b; Holding-Anyonge *et al.*, 2003; Clarke, 2005). Other studies have associated these sawing systems with the potential to expose the operators to a variety of occupational risks including musculoskeletal disorders (MSDs), hand arm vibration (HAV) as well as noise (Calvo, 2009). However, most of these studies have not attempted to make improvements. In addition, there has not been any reported attempt to optimize the operating conditions for these sawing systems. With saw mills inability to collect and saw farm trees due to the uneconomical distances involved, farmers are left with these inefficient systems as the only alternative for sawing their trees into timber, lest they sell them for fuel wood at the best (Kambugu *et al*., 2010).

This study was therefore conducted to evaluate and compare the efficiency of on-farm timber sawing systems used in Kenya and demonstrate enhanced eco-efficiency of one of the systems through optimization of the machine design parameters using empirical approach. This was aimed at developing an appropriate sawing system that can convert logs efficiently at low operation costs and improving livelihoods, while enhancing environmental protection as well as ergonomic characteristics.

1.3 Objectives

1.3.1 General Objective

The general objective of this study was to optimize on-farm timber sawing system using empirical approach for eco-efficient sawing of timber.

1.3.2 Specific Objectives

1. To assess the performances of on-farm timber sawing systems used in Kenya.
2. To determine the optimal design parameters for a selected timber sawing system based on empirical approach.
3. To evaluate the performance of the optimized on-farm timber sawing system and compare with the freehand chainsaw.

1.4 Research Questions

(i) How do the on-farm timber sawing systems used in Kenya compare in performance?

(ii) Can empirical approach be used to determine the optimal design parameters of on-farm timber sawing systems?

(iii) How does the performance of the optimized on-farm timber sawing system compare with freehand chainsaw?

CHAPTER TWO
LITERATURE REVIEW

2.1 On-farm Timber Sawing Roles and Practices

On-farm timber sawing is the on-site conversion of logs into timber using simple and movable sawing equipment (Fehr, 2006). Several techniques and types of equipment are used with a range of products produced and sold directly to the market while others are produced for further processing in sawmills. The emerging trends on the use of small-scale sawing systems in many countries have enhanced livelihoods under the remit of sustainable forest resource management and utilization (Wit *et al.*, 2010). These systems are useful in sawing isolated trees outside forests, especially on farms and in difficult terrain. The possibility of making a reasonable living from on-farm timber sawing and the scarcity or lack of other viable livelihood alternatives, particularly in rural areas are cited as powerful drivers for people to get involved in the practice (Muthike *et al.*, 2013; Marfo, 2010).

On-farm timber sawing is a typically representative of informal forestry processing sector (Hunt, 2002; Saigal *et al*., 2002). Sometimes, this sector is recognized as a key player behind illegal processing of timber in many poor countries, being difficult to regulate through law enforcement and monitoring (Tacconi *et al*., 2003). In Kenya for example, the Government has tried enforcing a requirement for a certification of tree ownership before felling them and a timber movement permit in an effort to control illegal logging in state forests and tree ownership conflicts among farmers (Muthike *et al*, 2010). More positively however, illegal logging and the use of portable sawing systems have been shown to be generally separate activities (Clarke 2005). A substantial part of the sector operates within the regulatory framework; legal operators make a considerable contribution to timber processing for domestic markets, and play a significant role in sustaining livelihoods in especially rural areas (Hunt, 2002; Saigal *et al*., 2002). Much of the available global review provides information from forested areas and temperate regions supporting the view that on-farm timber sawing could be economically viable in various situations, increasing revenues for tree farmers, sawyers and timber traders, and reducing negative environmental effects mainly from reduced forest cover (Richard and Rudy, 2010). However, these may not always occur in every situation, especially if the technologies are used are inefficient and are used without control (Wit *et al.*, 2010; Fehr & Pasiecznik, 2006).

There are three timber sawing systems; bench, chain and pit saw that have been used on farms in Kenya and other countries (Wit *et al*, 2010; Pasiecznik *et al*, 2006; Muthike, 2007). The chainsaw is more preferred because it is faster than pit saw and requires only one operator and at most an assistant. Its initial investment outlay is relatively lower compared to other motorized sawing systems. Due to its portability, chainsaw is less limited by terrain than bench saw and can be used to process even a single tree at a time. Bench saw is used in areas accessible to a tractor and where trees are available in relatively large quantities to enable economical operation before moving the equipment to a new location (Wit *et al.*, 2010). As trees get more scattered and distances increase, bench sawing become less economical (Oksanen *et al.*, 2002). Pit sawing is an old technology used in areas where trees grow in isolation on steep terrains and particularly where other sawing methods are unavailable. Being manually operated, pit sawing is slow and uneconomical (Pasiecznik *et al.*, 2006[a]). Both bench and pit sawing systems have therefore been continually replaced by the more versatile chain sawing system in many countries where small-scale timber processing is practiced either in or out side forests (Wit *et al.*, 2010).

Although these sawing systems have been criminalized, discussion forums and policy think-tanks are gradually conceding that they have great potential to contribute to poverty reduction strategies, particularly in rural areas where other employment options are few (Pasiecznik *et al.*, 2006). Examples from some countries indicate that government regulations are unlikely to have much impact on their own, so alternative approaches are proposed to mitigate detrimental effects (Wit *et al.*, 2010). These are based on ensuring clarity of laws and their enforcement as well as training and certification of sawyers (Holding-Anyonge *et al.*, 2003). Studies have shown that the on-farm sawing systems have fewer negative impacts on the sawing site than formal saw milling equipment, since the trees are sawn at the stump site (Muhumuza *et al.*, 2007). In formal sawmilling, logs have to be rolled and/or skidded, thus causing damage to young trees and other flora as well as interfering with the soil structure (Stanford, 1993).

2.1.1 Choice of On-farm Timber Sawing Systems

The characteristics of raw materials play an important role in the choices of the sawing systems to be used (Odoom, 2005). The aspects to consider when selecting appropriate timber processing systems include: access to trees and their available quantities and stem quality, machine production rate, available capital, and level of skilled labour (Pasiecznik *et al*., 2006). When trees are in plentiful supply, large-scale static sawmills with highly mechanized sawing equipment, able to process tens or hundreds of cubic metres of timber per day are likely to be more applicable. In Kenya and many other countries, many saw millers accessing saw logs in large quantities from state forests have invested in such machinery (Agus *et al*., 2010). More flexible systems may include the semi-static that can be dismantled and moved with little effort. The production economics however, demand that a certain amount of timber has to be sawn to ensure profitability before changing the location. Good examples in this are the movable bench saws and the narrow band saws (wood mizers). These are becoming common in the saw milling sector in the recent years (Guillaume *et al*., 2010).

Then there are the light-weight and portable systems, generally considered the most appropriate for areas where trees are scattered, standing timber volumes are low and access may be limiting (Hewit, 2005). Sawing machinery suitable in situations with such low production must be relatively light and able to efficiently convert small diameter, short and sometimes crooked logs. They should also be relatively low in capital cost to be economical if sawing only low volumes of timber per unit time.

Chainsaws are the best known example in this category. They have shown enormous potential for low volume farm forestry applications (Pasiecznik, 2000). A study by Wyatt (1996), concluded that chain saws were more appropriate for situations where selective harvesting was needed like on farms. Chain saw has been used in many countries as freehand sawing systems (Wit *et al*., 2010).

Chainsaw is the most widespread method of sawing timber at the artisanal on-farm level in many developing countries including Kenya (Pasiecznik *et al.,* 2007; Muthike *et al.,* 2010; wit *et al.*, 2010). It is mainly used freehand without any mechanism to guide cutting tool into the wood. Operators have a tendency of removing the cutter depth gauges to increase sawing speed. This practice makes the saw more aggressive and increases vibration, which reduces the operator's ability to control the machine (Pasiecznik *et al.*,2007). As a result of the cutter aggressiveness, vibrations and the back and forth mode of sawing, the saw path through the wood is increased, contributing to increased waste, rough surface finish and irregular timber dimensions. Freehand sawing uses only the tip of the bar, which engages only two or three cutters at a time during sawing. This increases resistance at the tip of the bar, which tends to push the chainsaw upwards and backwards, a phenomenon referred to as kickback. Kickbacks are serious ergonomic phenomena, responsible for many accidents in chain saw operations (Salafsky *et al.*, 1995).

While the use of chainsaws as sawing equipment in many countries is a common practice, a number of policies have also been tried to control and regulate the use of these systems but with limited success (Wit *et al.*, 2010). In Uganda, timber production regulations restrict the use of chainsaws for felling and cross-cutting operations, while it is illegal to use them for freehand sawing operation. They are only permitted as sawing equipment if the owner/operator uses frame attachments, registers with the National Forest Association with payment of the relevant fees (Kambugu *et al.*, 2010). In Ghana, although the use of chainsaws for commercial timber sawing is prohibited by law, the practice continues to thrive, providing direct jobs for about 130,000 people and livelihood support for about 650,000 more (Marfo, 2010). The inability of the conventional sawmills industry to supply the domestic demand with legally sawn timber remains the principal driver not only for chainsaw operations but also for illegality in the timber industry in general.

2.1.2 On-farm Timber Value Chain

In Kenya, unlike natural and plantation forests, which belong to the government and are managed through Kenya Forestry Service (KFS), trees grown on farms are privately owned by farmers, who either planted or inherited them. For most of the farmers, tree growing is a subsidiary activity to crop farming and little value is attached to them (Wamahihu, 2008). With farmers not well informed on tree valuation and value addition, most of them sell standing trees, generating little value. Price negotiations depend on the urgency of the farmer's need for money, tree quality and accessibility to the buyer (Pasiecznik *et al*., 2006). Farmers are approached by several types of buyers. These include private individuals, who require timber for projects. They hire sawing equipment and operators to saw the trees into the desired dimensions and sell the sawn timber to other dealers or end users. Others are timber brokers, who buy standing trees from farmers and sell them still standing to processors, making a profit without any physical effort (Pasiecznik, 2010). They usually offer the lowest prices for the standing trees. In such scenario, the farmers neither get full value of the trees nor do they have power over how they are being processed. This has been seen as one of the reasons for farmers not finding tree growing a lucrative supplemental activity on their farms (Ferh & Pasiecznik, 2006).

Among timber sawyers on farms, a variety of machine ownership structures exist. Some people purchase sawing machinery and employ operators. When a sawing job is found, the machine owner provides fuel and lubricants and charges the tree owner for sawing, based on linear measurement of sawn timber. The payment received is shared in three equal parts: two thirds go to the machine owner as payment for cost of fuel and maintenance of the machinery and profit. The other third is shared between operator and the assistant at a ratio of 2:1 (Pasiecznik *et al*., 2006). Some operators buy their own machines. In such cases, the sawing charges are paid directly to them and they employ assistants only when a job is found. The assistants are mainly paid based on the period of time they work. In some isolated cases, machine owners rent their equipment to operators for a fixed rate per day (Pasiecznik, 2010). In all the cases outlined here, once farmers sell their trees, they have no power to determine how they are processed. This coupled with lack of structured operations in the sub-sector and high demand for sawn timber encourages negligence to product quality, timber recovery and environmental protection as well as the safety of the operators. Such has been a major contributor to the decrease of trees on farms and environmental degradation (Holding-Anyonge *et al*., 2003).

2.2 Theoretical Review of Timber Sawing Systems

2.2.1 Performance of Timber Sawing Systems

The need for sustainable utilization of saw logs, their rising cost, and increasing demand for wood products are some of the reasons why the efficiency of timber sawing systems must be understood and improved (Pasiecznik, 2010). Conversion efficiency is highly variable, as it depends on a large number of factors, including the skill of the operator, the timber size to be cut and sawing pattern used, defects in the tree, size and shape of the log, species-specific differences in processing characteristics, and the basis used to calculate volumes and conversion factors. For ease of reconciliation of data on timber sawing systems, timber recovery is the most commonly reported (Marfo, 2010). Typical sawn timber recovery for a 1st quartile softwood sawmill with an average log top diameter of 150- mm would be distributed as 47% sawn timber, 34% off cuts, 9% saw dust, 6% size deviation and 4% shrinkage allowance (Hewsaw, 2013).

The most common way of determining conversion efficiency of a sawing system involves determining the system timber recovery and rate of timber sawing (Owusu *et al.,* 2010). More detailed analyses however include investigating the system production economics and ability to saw timber consistently within specified thickness and surface smoothness standards (Steele, 1984). Two basic factors that affect timber recovery, surface quality and dimension accuracy include the human capability to determine the correct machine settings and the mechanical capability of the machine to produce timber within given tolerances. It has been shown (Steele, 1984), that a sawing system having tightly set cutting tools can saw timber, closer to the target dimensions than a system with loosely set cutting tools. Figure 2.1 shows an ideal green sawn piece of timber with the appropriate dimensional allowances.

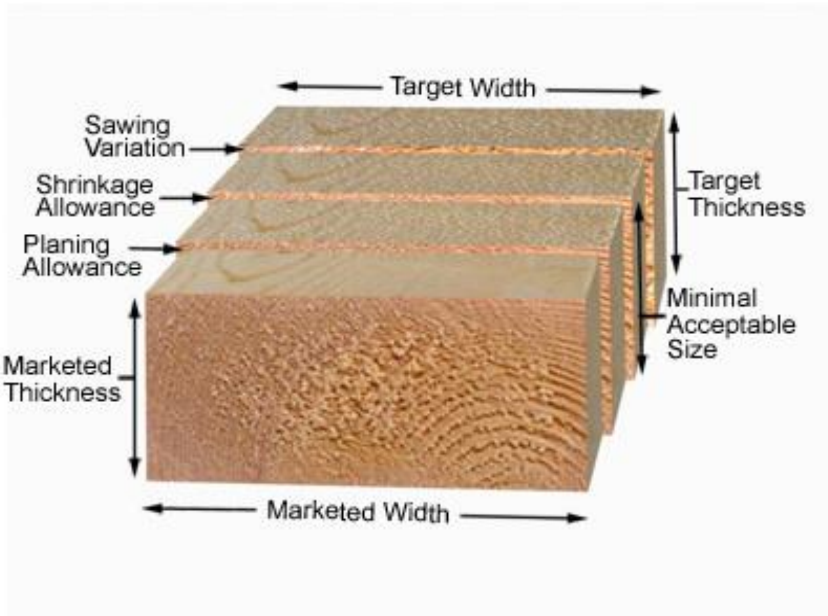


Figure 2.1: Considerations for timber dimensions.

The green target size must allow for sawing deviation, which can vary from one equipment to another ranging from±0.375-mm to ±1mm for standard sawing systems like band saws and other automated sawing systems (Hewsaw, 2013). Other allowances include wood shrinkage, which varies by species and moisture content and is normally less than 1.25mm per face. Reduction of saw kerf and sawing deviation allow for decreased green target sizes which increases timber recovery. Sawing systems that can allow for such accuracy not only save the raw materials, but also lead to higher monetary gain. However, each sawing system and its cutting process is unique in nature with no sawing system able to produce timber consistently at a specified target dimension without some variations between the boards (Steel, 1984). All sawing systems therefore include plus or minus tolerance around their target size to allow for these variations. The amount of tolerance to be allowed depends on the market and the prevailing standard requirements (Steel, 1984).

Other factors that determine tolerance in sawn timber include the nature of stress in the wood (Chikamai *et al.*, 1996), condition of the sawing equipment and the sawyer's expertise and experience (Stanford, 1993). With this tolerance included, it is expected that a good sawing system should maintain the size of the timber as close to the target dimensions as possible. A sawing system that produces timber with irregular dimensions along the piece or variations among pieces affects recovery due to under sized timber being rejected in the market while oversize timber carrying excess materials which cannot be accounted for. In trying to achieve the ideal situation and under fear of producing undersized timber, many sawyers set the sawing machinery to include more material in the target dimensions (oversize). This is a common scenario in on-farm sawing systems, which contribute to lower timber recovery. Other sawing systems used on farms also exhibit difficulties in adjustments to produce timber to the required dimensions.

Along with timber dimensions, variability in surface roughness is equally important. Surface roughness is defined as the measure of the irregularities of a surface of a material, in this case sawn timber. The size and frequency of these irregularities establish the surface quality and defines how a surface feels, looks and works when in contact with other surfaces (PDI, 1998). Sawn timber surface quality is of particular concern to users who have to subject the timber to further machining to improve the surface for specialized applications. Reducing the roughness of timber surface usually increases manufacturing costs exponentially due to use of more sophisticated cutting tools and the subsequent maintenance costs. This often results in a trade-off between the manufacturing cost of timber and its performance in application.

The level of roughness in timber surface is a factor of both the wood properties and the cutting tools used during sawing (Cassens & Feist, 1991; Richter *et al*., 1995; Barbu *et al*.,2000). Wood natural properties (anatomical, physical, mechanical and even chemical) vary considerably, not only between different species, but even among trees in the same species and along the tree height, within the same tree (Chikamai *et al*.,1996). Wood anatomic structure causes a first-degree texture comprising of tracheid or vessel diameter and cell wall thickness (Mutuku, 1981). A second-degree texture results from the machining method used in processing timber, especially marks and waves created by saw cutters or planer knives. Third-degree texture results from variation within the machining method resulting from vibrations due to misalignment and/or cutting tool characteristics (Ward and Gilbert, 2001). Irrespective of its cause, timber surface roughness is usually undesirable but difficult and expensive to eliminate.

Surface roughness (Figure 2.2) is not a commonly measured indicator in many saw mills particularly in developing countries. When measured, surface roughness, denoted as (R_a), is a quantitative calculation of the relative roughness of a linear profile or area, expressed as a single numeric parameter. Surface tracing equipment have been used and a roughness value either computed on a profile or on a surface. The profile roughness parameters (R_a and R_q) are more commonly used (Whitehouse, 1994). In a surface represented as shown in Figure 2.2, R_a and R_q are computed as;

$$R_a = \frac{1}{l}\int_0^l |Z(x)| \, dx \tag{2.1}$$

$$R_q = \sqrt{\frac{1}{l}\int_0^l Z^2(x) \, dx} \tag{2.2}$$

Among the two parameters, R_a, is by far the most common, measured in micro-meters (µm) (Östman 1983).

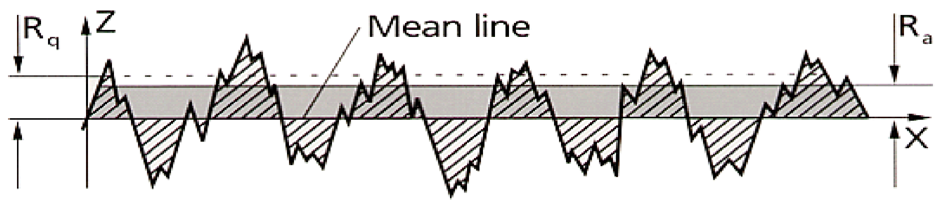


Figure 2.2: General material surface characteristics.

In on-farm timber sawing, controlling timber dimensions and surface roughness is a major challenge. Some of the sawing systems used for sawing timber like chainsaws were not designed for the purpose. Their mode of operation and the subsequent behavior, particularly vibration allow for reduced dimensional uniformity, timber recovery and increased surface rough surfaces. Their applications in sawing timber to commercial sizes therefore need modifications to accommodate the new application if timber recovery and surface quality are to be enhanced to similar or close levels to the sawn timber sawn using acceptable commercial sawing machinery.

a) Chainsaw Cutting Tools

For general use in forestry and tree felling, two basic chain configurations; felling ans splitting chains exist. Felling chains use the full chisel square cornered cutters, like a number "7" with a sharp top-right corner (α = 15-20^0). These are usually aggressive and efficient in cutting across the wood fibers. Splitting chains use semi-chisel teeth, which have more or less rounded working corner formed by a radius between the top and side plates making a larger cutting angle (α = 25-35^0) (Oregon, 2004). While slower than full chisel, semi-chisel cutters retain an acceptable cutting sharpness longer. Due to their fairly dull edge, many more cutters can be engaged at a time without adversely slowing the engine. These chains are usually used in framed chain sawing systems. In addition, while in freehand sawing, the chain depth gauges are totally removed, in framed chain sawing, they are periodically reduced to keep the cutters from digging too deep into the wood, thus reducing vibrations hence keeping the timber surface smooth and dimensions uniform (Pasiecznik, 2010). Such chains are not commonly available on the market in most developing countries including Kenya, where the use of chain sawing is less developed. In these countries, felling chains, used for felling and crosscutting wood dominate the market. These are the ones currently used for freehand chain sawing.

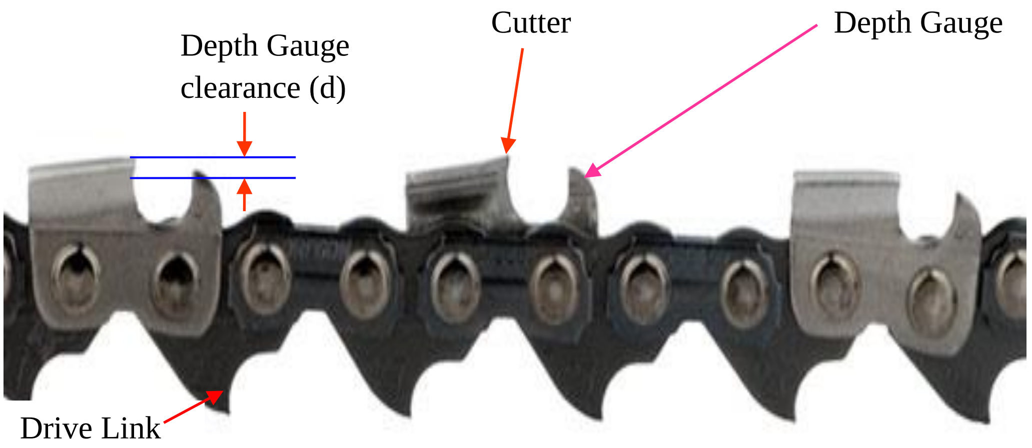


Figure 2.3: Parts of a chain, cutting angle and depth gauge.

b) Chain Working Principles

The cutting tool in the chainsaw equipment (chain) is driven by drive links, which ride on the sprocket, the driving component on the engine. During sawing, depth gauges ride on the wood and control the depth at which the cutting corner bites into the wood material. This helps to control the sawing speed and machine vibration. The cutting corner and side plate sever the wood grains. The top-plate cutting angle chisels out the severed wood fibers, lifting them up and out of the kerf. The gullet pocket carries the removed material (saw dust) and takes it out at the turning of the cutter. Cutters take turns biting as they porpoise through the cut propelled at high speeds by the sprocket. Depth gauges are typically set at heights lower than the tip of the corner. It is this difference between the tip of the top-plate and the height of the depth gauge, referred to as the depth gauge clearance that enables or prohibits the cutter to/from biting too deep into the wood (Oregon, 2004).

When the depth gauges are allowed longer than necessary, thus leaving a smaller clearance, they prohibit the cutters from digging into the wood. They only slide on the wood without cutting, which results in fuel usage but no work done. When set too short or totally removed, thus with large clearance as is the case with free hand chain sawing, the cutters can dig too deep into the wood. This however tends to stall the engine and introduce vibrations. Based on the above principles, when felling chain cutters are used for splitting timber as in the freehand chain sawing with removed depth gauges, the cutters take deep bites into the wood aided by the sharp cutting angle (α) and no depth gauges to control the cutting depth (d is large). Sawyers therefore use only the tip of the chain bar, thus engaging only a few cutters (Muthike *et al*., 2008). This permits the engine to drive the few engaged cutters to achieve high sawing speed. It however tends to increase vibration. Excessive vibration is the main cause for undesirable noise, variations in timber dimensions and rough timber surface. They also contribute to the increased waste due to the widened saw path (Pasiecznik, 2010). Chainsaw operators are also likely to be exposed to the increased Hand-Arm Vibrations (HAV) emitted from the machine (Bovenzi, 2003).

Figure 2.4: Freehand chainsaw system.

2.2.2 Effect of On-farm Timber Sawing Systems on the Environment

Kenya's environment, like most other countries has suffered from the impacts of human activities. Deforestation, land degradation, and water pollution are some of the challenges the nation needs to address in order to achieve the envisaged goals stipulated in the Vision 2030 (GoK, 2007). However, a number of social and political factors continue to put pressure on natural resources and compromise the effective implementation of sustainable environmental development strategies in Kenya. They include limited government capacity for environmental management and insufficient institutional and legal frameworks for enforcement and coordination (FAO, 2010). Kenya is one of the least forested countries in sub-Saharan Africa with forests covering only 37.6 million ha, about three per cent of total land area (FAO, 2010). Between 1990 and 2005, the proportion of forested land in sub-Saharan Africa dropped by three per cent, from 29 to 26% while the same period, Kenya's proportion of forested land decreased by 0.3%. Similarly, between 1990 and 2003, 186 000 ha of forest land was lost through excessive timber harvesting and forest land being converted to other uses (Thaxton, 2007). This resulted into biodiversity loss, with possible irreparable consequences for ecosystem services, food security, and tourism, all of which make significant contributions to Kenya's economy.

Kenya aims at being a nation with a clean, secure and sustainable environment by 2030. The immediate goals are to attain a forest cover of 10% and to lessen by half all environment-related diseases. The specific strategy involves promoting environmental conservation in order to provide better support to the economic pillar flagship projects (GoK, 2007). These include reduction of air and water pollution, improvement of waste management through the design and application of efficient industrial processing systems and provision of economic incentives to encourage investment in the same. In addition, the country hopes to harmonize environment-related laws for better environmental planning and governance. The achievement of these aspirations is likely to be delayed due to environmentally unfriendly and inefficient systems like those currently used in on-farm timber sawing. Low timber recovery implies that more trees are being cut to supply the ever increasing demand for sawn timber.

a) Solid Wastes in Timber Sawing

Apart from deforestation, sawing of timber generates solid by-products, which become sources of pollution and other hazards like fire. The amounts of these by-products from a given sawing system illustrate the level of inefficiency of the system. In an efficient sawing system, the distribution of sawn timber and by-products takes the proportions illustrated in Figure 2.5. Although the proportions may vary among systems, dimensioned timber takes much of the material, followed by off cuts (chips) and saw dust. A small allowance is also included on the dimensioned timber for shrinkage, when the timber loses moisture after sawing. While off cuts are inevitable during sawing because of the circular nature of the logs, they can be reduced through precisely converting the large ones into dimensional timber if an accurate sawing system is applied. All timber sawing machinery are a source of these by-products at varying quantities, which is a factor of the machine inefficiency in converting round wood into sawn timber (Stanford and Lunstrum, 1993).

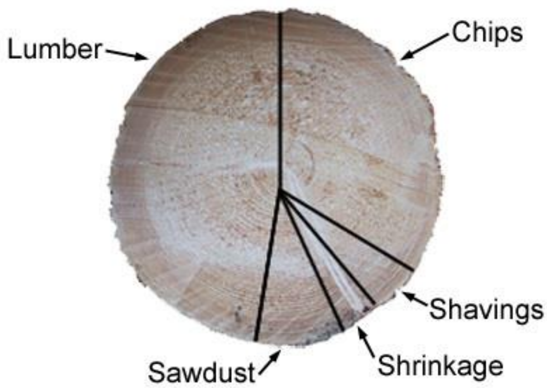


Figure 2.5: Distribution of sawn timber and by-products.

Saw dust is caused by the saw path. During sawing, the saw teeth bite into the wood tearing the material into dust. The amount of this dust is usually proportional to the size of the saw path, which is further dictated by both the kerf and the vibration of the saw during sawing exercise. Wood shavings on the other hand are as a reason of the allowances included to the dimensioned timber for planning. This allowance can be larger than necessary, contributing to low timber recovery when inefficient sawing systems and vibrating saws are used. These also add to the solid wastes to be dealt with (Stanford & Lunstrum, 1993).

In developed countries, offcuts are not considered as wastes because they are easily further processed into chips particularly for pulp or energy applications. However, in Kenya and many other developing countries, offcuts are mainly sold to the local population as fire wood without further processing. Although in rural areas where a large percentage of the population use wood for their domestic fuel requirements (Githiomi *et, al*., 2012), off cuts are not a major challenge, in areas where the local population can access cheaper or free fire wood from forests, saw mill offcuts find no market and become a menace due to challenges in storage. Heaps of off-cuts are easy to notice in many saw mill setups across the country (Muthike *et al*., 2013). Large heaps of saw dust are a common scene in saw mill compounds, most of it being burned because it doesn't have immediate commercial use. Burning saw dust, like any other biomass material increases emissions of air pollutants into the atmosphere.

Although small-scale utilization technologies for saw dust have been developed, their uptake and application have been slow and so far are unreliable in reducing the quantities of saw dust (Githiomi *et al*., 2012). The challenges associated with the utilization of by-products from timber sawing therefore calls for precision to reduce them and particularly at the sawing stage. This can be incorporated in machine designs in an effort to transfer the materials in these wastes into sawn timber, increasing recovery.

b) Gaseous Emission from Timber Sawing Systems

Worldwide, carbon dioxide (CO_2) emissions reached 2900 million metric tonnes in 2004 and they continue to rise from increasing concentrations of CO_2 in the atmosphere. Per capita CO_2 emissions in sub-Saharan Africa were 0.9 metric tons between 1990 and 2004. This is less than one-tenth of the per capita CO_2 emissions in the developed world (UN 2000). Kenya's per capita emissions are much lower than the sub-Saharan average, although there was a slight increase from 1990 to 2004 (UN 2000). Nevertheless, CO_2 pollution, resulting mainly from industries and the increasing number of motor vehicles on Kenyan roads, is one of the leading environmental health problems in the country affecting both rural and urban populations (GoK, 2007). Timber industries particularly those using fossil fuel-driven engines contribute to environmental pollution.

Small gasoline-powered engines and tools present a serious health hazard. They produce high concentrations of carbon monoxide (CO), a poisonous gas that can cause illness, permanent neurological damage, and death. Because this gas is colorless, odorless, and non-irritating, it can overcome exposed persons without warning. Often there is little time before they experience symptoms that inhibit their ability to seek safety. Prior use of equipment without incident has sometimes given users a false sense of safety, with such users being poisoned on subsequent occasions. The use of gasoline-powered engines or tools can therefore only be considered safer if used in open areas where fresh air circulation is guaranteed. There would also be need to study the emission levels of these systems to enable meaningful recommendations on their use and the appropriate personal protective equipment (PPE) (UNEP, 2004).

2.2.3 Ergonomic Characteristics of Timber Sawing Systems

Ergonomics is the scientific study of human work conditions. In timber sawing, ergonomics deals with the interaction between man and machine. It is concerned with the 'fit' between people and their technological tools and the working environments (James, 1993). Ergonomics takes account of the user's capabilities and limitations in seeking to ensure that tasks, equipment, information and the environment suit the user. To assess the fit between the user and the technology used, ergonomics consider the activity being done and the demands on the user; the equipment used (its size, shape, and how appropriate it is for the task. Ergonomic Analysis of Work (EAW) is the main tool of the activity-centered ergonomic interventions. It analyses and evaluates worker’s posture at different levels of the activities. It helps to solve numerous problems related to working conditions or the design of tools and equipment (Licht *et al.*, 1989).

The most common risks associated with small-scale timber sawing systems are Musculoskeletal Disorders (MSD) and Hand and Arm Vibration (HAV) (Bovenzi, 2003). MSDs are usually caused by poor working posture and lifting of weights, which can cause back disorders. Back injuries result from damage, wear, or trauma to the bones, muscles, or other tissues of the back. Common back injuries include sprains and strains, herniated disks, and fractured vertebrae. While the lumbar area is susceptible to pain because of its flexibility and the amount of body weight it regularly bears (Farfan, 1973). Low-back pain is often the result of incorrect lifting methods and posture. Repetitive lifting, bending, and twisting motions of the torso affect both the degree of severity and frequency of low-back pain. In addition, low-back pain may also be the result of bad lifting habits. It is estimated that low-back pain may affect as much as 50 to 70 percent of the general population in the United States (Wickens *et al*., 1997).

Vibration refers to mechanical oscillations about an equilibrium point (ISO, 1997). In production, vibration is undesirable, wasting energy and creating unwanted noise. For example, the vibrational motions of engines, electric motors, or any mechanical device in operation are typically unwanted. Such vibrations can be caused by imbalances in the rotating parts, uneven friction and the meshing of gear teeth among others. Careful designs usually minimize unwanted vibrations. Such vibrations are also harmful to the machine operators’ health particularly where the machine comes in contact with the operator's body (Lewark, 2005).Vibrations like those transmitted to the human hand-arm (HAV) system and whole-body vibrations (WBV), entails risks to the health and safety of workers, in particular vascular, bone and/or joint, neurological or muscular disorders (Calvo, 2009). Whole body vibrations (WBV) are mainly caused by large machines like tractors and skidders and are not common with small hand held machines (Ashby *et al*., 2001; Bovenzi, 2003; Waters, 2004).

2.2.4 Economic Evaluation of Timber Sawing Systems

With reports showing that the available sawing systems as inefficient (Holding-Anyonge *et al.*, 2003), it is important to investigate whether investing in them is a viable venture and under what conditions would the sawing system yield maximum profitable benefits. Viability in this case is not only an incentive for converting the trees into sawn timber but also a justification for planting more trees. Like in any other investment ventures, economic evaluations are necessary to evaluate the financial viability of such sawing systems (Zimmermann, 1985; Changwe, 1991; Ongugo, 1992). It also provides a guide in choosing between two or more potential sawing systems as well as indicating the conditions under which the best sawing system can operate to maximize returns. Presently this information is scarce in on-farm timber processing sub-sector and what is available is scanty on detail costs and benefits from target systems.

Evaluation and optimization of economic performance of timber sawing systems analyzes various aspects that related to economics of timber processing using both descriptive and quantitative economic analytical procedures (Samuel *et al.*, 2007). Collected data is compiled and analyzed using a variety of analytical tools and fed into economic models. Ordinary Least Squares (OLS), averages and percentages are then applied where necessary with a two-dimension matrix used to analyze and rank the sawing systems. To determine profitability, cost-benefit approach is used, in which total profitability Л (T), which is a function of the quantities (Q) of inputs and accrued income are represented by the following equations.

$$Л(T) = Л(Q) = \mathrm{R}(Q) - \mathrm{C}(Q) \tag{2.3}$$

and;

$$Л(\mathrm{T}) = P_y f(x_{it}, q_{it}) - \sum_1^n e_{it}\,(x_{it});\ \ \mathrm{i} = 1,2,3,\ldots\ \mathrm{n} \tag{2.4}$$

In the equation, $f(x_{it},q_{it})$ is the returns function; e is a price vector for inputs ($x_i....X_n$) used in on-farm timber sawing and P_y is the on-site price of sawn timber. The output (q), which in this case is the timber production rate for the sawing system, is influenced by the system sawing characteristics and applied inputs. The economic benefits are therefore represented by;

$$\mathrm{G_I} = \mathrm{QP_y} \tag{2.5}$$

whereG_I is the gross income and QP_y is the gross output, given by quantityQ in volume, and the on-site price (P_y) of the sawn timber. The total cost (C_x) used in on-farm timber sawing is considered as summation of the costs of input materials, labour and capital equipment and was summarized as shown in equation (2.6). In the equation, M is materials cost, L is labour cost, and D is depreciation cost on equipment.

$$\mathrm{C_x} = \sum(\mathrm{M} + \mathrm{L} + \mathrm{D}) \tag{2.6}$$

The Net Present Value (NPV) and Annual Equivalent Value (AEV) are used to carry out financial investment analysis. The Net Present Value is the present value of all benefits (revenues) less the present value of costs, which is expressed as:

$$\mathrm{NPV} = \sum_1^n\{(\mathrm{B_t} - \mathrm{C_t})/(1 + \mathrm{r})^{\mathrm{t}}\} \tag{2.7}$$

In the equation B_t is benefit in each year, C_t is production cost in each year, t is time period, n is the rotation period and r is the discount rate. Annual Equivalent Value (AEV) combines all costs and benefits into a single sum that is equivalent to all cash flows during an analysis period spread uniformly over the period. It is an annual payment that will pay off the NPV of an asset during its lifetime, i.e.

$$AEV = NPV\{r(1+r)^t\}/\{(1+r)^t - 1\} \qquad (2.8)$$

In such scenario, to maximize profits, which is the aim of sawing logs into timber,

$$P \geq R - C \qquad (2.9)$$

where, the gross profit *P* is the difference between the cost of sawing timber(*C*) and the revenue (*R*) from the sales of the final timber sawn.

Given a period of time for which sawing takes place and cash flow involved in the process, the rate of return for which this function is zero is an internal rate of return. In this case, given the (period, cash flow) pairs (n, C_n) where n is a positive integer, the total number of periods N, and the net present value NPV, the internal rate of return is given by r in:

$$NPV = \frac{\sum C_n}{(1+r)^n} = 0 \qquad (2.10)$$

Note that the period is usually given in years, but the calculation may be made simpler if r is calculated using the period in which the operation is defined (e.g., using months if most of the cash flows occur at monthly intervals) and converted to a yearly period thereafter.

2.3 Empirical Review

2.3.1 Performance of On-farm Timber Processing Systems

Chain sawing, operated freehand has been reported in a number of studies In a study using farm grown trees, high log conversion rate by chainsaw system was attributed to the ability of the system to convert very small diameter and poorly (crooked) shaped logs than the other systems (Samuel *et al*., 2007). In another study in Ghana, involving a variety of tropical hardwood species and a number of sawing systems, Owusu *et al*. (2011), reported that chain sawing recorded higher log conversion rate (mean 75%) than wood mizer system (68%). Similar results are reported in the same country by Marfo (2010). However, both studies reported that sawyers tended to leave out smaller diameter logs unprocessed due to abundance of wood in tropical forests unlike Kenya where round wood is in short supply. In such cases, sawyers try to maximize on the available materials, irrespective of the sawing system being used.

Unlike large-scale industrial harvesting and processing techniques, in small-scale timber sawing, a large amount of wood is lost in form of sawdust, off cuts and oversized timber dimensions resulting in low sawn timber recovery, rough surface and irregular sizes (Muthike, 2004). Because of these irregularities, users have to specify larger dimensions than required to allow for excessive planning needed to obtain consistent dimensions and acceptable surface finish (Pasiecznik *et al*., 2006). This too contributes to financial losses with much more material included in the timber dimension and latter planned off, requiring more time and energy.

Several authors acknowledge that the use of obsolete sawing techniques has contributed to these inefficiencies (Pasiecznik *et al*., 2006; Marfo, 2010; Wit *et al*., 2010). In Kenya, there have only been a handful of studies on timber sawing systems efficiency and all have concentrated on timber recovery while ignoring other critical aspects of efficiency in timber sawing (Muthike *et al*., 2008). Kihuru (2009) reported timber recoveries of 35-40, 20-25 and 10-20% for the large, medium and small-scale sawmills respectively, which compares well with data reported for bench saws used on farms (Marfo, 2010; Muthike *et al*., 2010). Muthike (2007) and Kiuru (2009) reported that most of the machine operators in on-farm timber sawing and small and medium enterprise (SME) saw mills are inadequately trained, which in part contributes to low timber recovery and poor timber surface irrespective of the sawing system used.

Other studies (Holding *et al*., 2001; Holding-Anyonge & Roshetko, 2003; Marfo, 2010) associated the inefficiency of these sawing systems with among others the system mode of operation, where no form of control mechanisms are used to guide the saw through the wood. These have been the cause of low timber recovery and rough surface (Owusu *et al*., 2011). Although it has been increasingly clear over the past decade that timber from farms is making up an increasingly significant proportion of locally available timber in many tropical countries, with little or no information, many sawyers have not been able to know which sawing system suits their condition (Jaakko, 2001; Pasiecznik, 2010). Modifications to the sawing systems are very rarely used and the 'technology' employed is the most basic, with inherent challenges related to a high risk of accidents and operator fatigue. However, there has been some trials of improved methods in the recent past in a number of countries (Samuel *et al.*, 2007). In chain sawing for example, frame attachments are becoming more widespread though, and the technology will surely evolve, with further novel adaptations which should be identified and assessed in their appropriateness in on-farm situations. The viability of such modifications should be evaluated and adopted for situations like what is currently in Kenya.

2.3.2 Effects of On-farm Timber Processing Systems on the Environment

The amount of solid wastes produced in saw milling industry differs with the type of cutting tools and their width. Although there was scanty information on the amount of wastes generated in saw mills, timber recovery is a good indicator of the level of wastes generated by different sawing systems. It is indicated that out of 30-40% overall wastes generated from timber sawing exercise, 15-17% are offcuts and edgings and the rest is saw dust (FPL, 1987). Kiuru (2009) estimated that most saw mills would release into the environment to the tune of 53-68% of their wood intake as solid by-products. A very small amount of this find some economic use, the rest being thrown away as wastes (Kilkki, R., 1993). For on-farm timber sawing systems, with timber recoveries of between 27 and 35% (Samuel *et al.*, 2007; Muthike *et al.*, 2008; Wit *et al.*, 2010), the solid wastes released to the environment would be to the range of between 65 to 73%. These statistics are good indicators of the effect sawing of timber have on the environment, which need attention.

Another emission to the environment resulting from timber processing is gaseous emissions. Studies in forestry operations have linked sawing machinery and other related activities with a number of environment-related risks in many countries. It is widely known that small gasoline-powered engines and tools present some health hazards. They produce carbon monoxide (CO), a poisonous gas that can cause illness, permanent neurological damage, and even death. Many people using gasoline-powered tools such as high-pressure washers, concrete cutting saws, power trowels, floor buffers, welders, pumps, compressors, and generators in buildings or semi-enclosed spaces have been reported poisoned by CO (US Dept of Health and Human Services, 1981). Carbon monoxide can rapidly accumulate (even in areas that appear to be well ventilated) and build up to dangerous or fatal concentrations within minutes. Because it is colorless, odorless, and non-irritating, CO can overcome exposed persons without warning. Often there is little time before they experience symptoms that inhibit their ability to seek safety. Prior use of equipment without incident has sometimes given users a false sense of safety, with such users being poisoned on subsequent occasions. On-farm timber sawing machinery particularly the chain saws fall in this category. Although they are operated in open air, this does not completely eliminate the risk of exposure to the poisoning gases especially due to the proximity of the operator to the machine. No studies were identified on efforts to reduce the emission of these gases.

2.3.3 Ergonomic Characteristics of Timber Sawing Systems

Regarding working posture and exposure to vibrations, studies have shown that, about 24% of all the European forestry workers report suffering from backache and 22% complain about muscular pains as a result of poor working posture (Calvo, 2009). Moreover, almost ⅔ of workers in Europe reported being exposed to repetitive hand-arm movements and ¼ to vibrations, which are significant risk factors related to machine operations, especially chainsaws (European Agency, 2008). In light of a comprehensive study, conducted by the National Institute for Occupational Safety and Health (NIOSH), the Institute concludes that vibrating hand tools can cause vibration syndrome, a condition also known as vibration white finger and as Raynaud's phenomenon of occupational origin (Calvo, 2009). Vibration syndrome has adverse circulatory and neural effects on the fingers. The signs and symptoms include numbness, pain, and blanching (turning pale and ashen). Of particular concern is evidence of advanced stages of vibration syndrome after exposures as short as one year. NIOSH recommended that jobs be redesigned to minimize the use of vibrating hand tools and that powered hand tools be redesigned to minimize vibration. Where jobs cannot be redesigned to eliminate vibrating tools such as pneumatic hammers, gasoline chain saws, and other powered hand tools, engineering controls, work practices, and administrative controls should be employed to minimize exposure (Lewark, 2005).

In timber production, most work-related disorders are as a result of repeated lifting of high or low intensity loads, repetitive bending and other body movements over a long period of time. Freehand chain sawing for example dictates that the logs are sawn on the ground. This demands that the operator bends throughout the operation, a practice that is likely to increase back straining. In such cases, application of machine design modifications like use of framed systems have been seen as one of the possible solutions towards reduction of the exposure to back bending and vibrations (Muthike *et al*., 2010; Samuel *et al.,* 2007).

The European Union Physical Agents directive EC/44 (ISO, 2001), specifies both practical limits for daily personal vibration exposure, and the lower levels above which steps should be taken to reduce exposure to vibration (ISO 1997). In the directive, hand-arm and whole body vibration levels are defined. Exposure limit values and action values are also established and standardized to an eight hour reference period. For hand-arm vibration, the daily exposure limit value (ELV) is 5 ms-2, while the daily exposure action value (EAV) is 2.5 ms-2. For whole-body vibration, the daily exposure limit value (ELV) 1.15 ms-2 and the daily exposure action value (EAV) is 0.5 ms-2. There is need therefore to analyze the new sawing system and compare its effects on the operators in terms of exposures to HAV and risks of MSD. While engineering solutions to reduce whole body vibration (WBV) levels experienced by agricultural vehicle operators are common, historically in the guise of improved design parameters like spring suspension seats and handle bars, they are only more recently in the form of cab and/or axle suspension systems for larger machines (Kanali *et al.*, 1996). In hand-held vibrating tools like those used for semi-mechanized operations; chainsaws, drills etc., attention should be focused on HAV.

Studies by the National Institute for Insurance against Industrial Injuries in Italy during the period 2002-2006, indicated that professional illness related to the MSDs were increasing. Other different groups of factors that are common in forestry operations and may contribute to development of these pathologies include difficult environmental conditions (low temperatures, slippery and uneven ground), heavy works (manual handling of logs and machines which cause flexed and twisted back), physical or biomechanical factors and organizational and psychosocial factors. Upper limb movements need attention among forest machines operators and a good analysis method of the problem is offered by the ODDs ratio. The ODDs ratio is one of a range of statistics used to assess the risk of a particular outcome, if a certain factor or exposure is present (Calvo, 2009). The ODDs ratio is a relative measure of risk, telling how much more likely it is that someone who is exposed to a given factor under study will develop the outcome as compared to someone else who is not exposed. This is estimated by the ratio of the number of times that the event of interest occurs to the number of times that it does not.

Another method, the Occupational Repetitive Action (OCRA) (Colombini, 1998) is specifically used for analysis of exposure to tasks concerning various upper limbs risk factors (loads, awkward postures, repetitiveness and lack of recovery periods). The method has been applied in different working sectors that involve repetitive movements and/or efforts of the upper limbs. It consists of an index calculated as the ratio between the actually technical actions carried out in the work as repetitive tasks and the number of technical actions (OCRA index) recommended (Occhipinti, 1998). The higher the OCRA index, more severe is the risk to develop into MSDs. In on-farm timber sawing, no studies in this regard were available for Africa. This could be attributed to the fact that these practices are still at non-commercial levels and very little attention is given to them.

2.3.4 Optimization of Timber Sawing Systems

Conversion of trees into sawn timber has been practiced in many countries in the world, with different sawing systems being tried. Over the past decade, timber sawn using small-scale systems is making up an increasingly significant proportion of locally available timber in many tropical countries (Holding *et al*, 2001). However, outside forests, low tree densities and volumes render many common sawing practices are unviable. Sawmilling machinery suitable in situations with such low production must be very portable, able to efficiently saw small diameter, short and sometimes crooked logs, and of low enough capital cost to be economical if sawing only small volumes of available materials. Small-scale sawing systems to include chainsaws, movable bench saws are among the few options that have been used although with challenges due to their inefficiency (Pasiecznik, 2010).Although available literature have reported inefficiency among these systems, data on their optimization and general improvement is scanty (Samuel *et al.*, 2007).

This scenario could be attributed to the fact that small-scale sawing methods are peculiar amongst saw milling techniques due to their high portability, low cost, and suitability for sawing logs that might otherwise be rendered useless. Recovery is therefore not so much of an issue as most of the wood would have become firewood anyway. Thus, even if only 10% of the wood could be converted to boards or beams, with a small value added per volume from fuel wood to sawn timber, sawing of at least the larger logs could make good economic sense if market can be found to cover the running costs. Attempts have been made to developing an understanding into the situations where these sawing systems may be viable with little success, due to particularly the dynamics of their operations (Samuel *et al.*, 2007). Their use in certain situations in general appears to be typical to small-scale operations, and does not offer much insight into current and potential applications (Pasiecznik, 2010).

Further still, the development and use of a variety of sawing systems over the past few decades, mainly on farms appears to have been driven mainly by hobbyists. These could have been people who seemed not to be time or capital-limited, often could access logs at very low cost if not free, saw infrequently, produced relatively low daily and annual volumes of timber and possibly did not earn their living from it (Pasiecznik, 2010). In such cases, the operators would neither worry about detailed economics of operations nor trying to optimize the operations. Even today, outside forests in the tropics and sub-tropics, the use of small-scale sawing systems is still in its infancy, though rapidly gaining ground. They are being used to process mainly agroforestry trees, such as shade trees including *Cordia alliodora* in Central America, boundary trees like *Grevillea robusta* and *Eucalyptus* along with dryland species such as *Acacia nilotica* and *Prosopis juliflora* in East Africa, and numerous species in West Africa (Marfo, 2010).

Some studies have been undertaken on the characteristics of, and the relative resources available to, groups involved in almost exclusively small-scale sawing of timber in natural forests in the humid tropics, e.g. Guyana (Clark, 2005b), Ghana (Odoom, 2005), Indonesia (Roda, 2005) and Vanuatu (Wyatt, 1996). However, No similar studies are reported on uses of these systems in temperate or developed country situations. There are also very few studies on small-scale timber sawing from outside forests in the tropics, possibly due to the much lower volumes of timber being processed, the marginal economic importance and thus less interest. Little has therefore been reported on particularly the economic performance of these sawing systems. Where studies have been undertake, comparisons have been mainly on the basis of their timber recovery and in fewer cases on timber production rates (Odoom, 2005, Owusu *et al.*, 2011).

The use of these sawing systems is however diversifying in the recent years. There is for example a developing market for renting sawing machinery and associated equipment both within and outside forests. Labourers have also been required to assist in felling, sawing and ferrying sawn timber from sawing site to the roadside. Although this is more part-time, and labour requirements may be met by family members or others with low opportunity costs, such as out of season agricultural labour, their costs are of significance when economic performance of the systems is evaluated.

The following tables present some of the available data on the sawn timber outputs and recovery rates from small-scale sawing methods. To allow for basic comparison between selected data from other portable saw mills conversion rates used included 8 hours in a working day with very low timber recoveries (Samuel *et al*, 2007). Figures quoted usually refer to output per working team, generally two to three people for chain saws and seven to nine for bench saws. Productivity is calculated as the volume of sawn timber produced, and not the volume of logs sawn. It is not always clear, however, whether recovery is from the whole log or just a squared cant thus this data should be treated with caution.

CHAPTER THREE
MATERIALS AND METHODS

3.1 Performance of On-farm Timber Sawing Systems

In order to compare the performance of the three on-farm timber sawing systems used in Kenya, log conversion rate, sawn timber recovery, fuel efficiency and timber dimension uniformity were tested. Wood used in this study included two species (*Eucalyptus saligna* and *Grevillea robusta*), commonly grown and sawn into timber on the farms particularly in high potential and semi-arid areas. A third species, *Prosopis juliflora*, was included to represent some of the difficult to saw hard wood species currently being promoted for their survival in the dry lands. In particular, *Grevillea robusta* and *Eucalyptus saligna* wood was sampled and collected from farms in Bahati area of Nakuru county, while *Prosopis juliflora* was obtained from research plots in Marigat, Baringo county, Rift Valley. Due to scarcity of mature trees on farms as a result of high demand, at least *Grevillea robusta* and *Eucalyptus saligna* trees of 20 years and over with relatively good stem form and minimum defects were sourced. *Prosopis juliflora* trees used were 30 years of age. Table 3.1 shows the characteristics of the trees obtained for these experiments. The properties of the wood species were also analyzed to determine their influence on the performance of the sawing systems.

Table 3.1: Mean characteristics of the table 3.1:mean characteristics of the tree species used in the study.

Scientific Name	Tree age (yrs)	Tree height (m)	Merchantable bore length (m)	Diameter (m)	*Density (kg/m^3)
E. saligna	25	16.72	12.54	0.36	639.67
G. robusta	20	11.70	7.35	0.29	529.99
P. juliflora	27	6.67	2.66	0.21	864.67

*Density is at 12-15% moisture content,

Trees were felled and cross cut using a chainsaw. A well maintained chainsaw, fitted with a new and appropriately sharpened chain was used in freehand chain sawing. A locally fabricated saw bench, driven by a tractor, was used for bench sawing. A trained and experienced sawyer operated the freehand chainsaw and also acted as the lead sawyer for the bench saw. Two operators with over 5 years' experience in pit sawing were sourced from the field to conduct sawing with pit saw system. They worked with their own saw blade, which was in serviceable condition. Table 3.2 shows the equipment used for the various sawing systems applied in the study.

Table 3.2: Specification for the sawing systems used.

Sawing System	Make/ Model	Engine Power (HP)	Fuel Type	Saw Type and Kerf (mm)
Chainsaw	Husqvarna 365	4.6	Petrol/oil mix	(chain) 9.5
Bench saw	MF 135 Tractor (3 years old)	20	Diesel	(circular saw blade) 7.5
Pit saw	N/A	Manual	Manual	(flat blade) 3

3.1.1 Data Collection Procedure

Trees from each species were randomly sampled and marked for each sawing system. After felling, total tree height was measured from the bottom to the tip of the crown using a measuring tape. The total merchantable bole length from the butt to the lowest diameter the particular sawing system could economically saw was measured, to determine the length of the merchantable portion of the stem that a particular sawing system could convert. Trees in the respective groups were crosscut into logs of lengths that are acceptable in the timber market, considering the capability of the sawing system to saw the length while minimizing on defects. Logs with the smallest diameter and length that a particular sawing system could economically convert were chosen and the rejected ones set aside. The volume of the logs obtained in each case and volume of the rejected ones were determined to evaluate the log conversion rate for each sawing system. Diameters were measured to the nearest centimetre at the butt, top and at every 0.5m intervals along the length of the logs using a diameter tape (ISO, 1983). This was used to compute the mean diameter for each log. Log lengths were measured to the nearest 0.01m using a linear tape. The total volume of the logs in each test was computed using Smalian Formula; Equation (3.1) (ISO, 1983), where V_l is the total merchantable log volume, L is the merchantable log length, D is the log mean diameter and π is a constant.

$$V_l = \sum\left(\frac{\pi D^2}{4} L\right) \quad (3.1)$$

All timber sawing was done on the felling sites in the respective areas to mimic the usual on-farm sawing practices and costs. Monkey jacks were used for turning the logs to facilitate log measurements and alignment during processing. Other items used for the study included saw chains, round files for sharpening saw chains, flat and triangular files for sharpening circular and pit saw blades. A stop watch was used to record time of the operations for purpose of computation of timber production rates. All timber sawing involved through and through method and produced timber of 150x25mm dimensions for purpose of this study. The total volume of the resultant sawn timber (V_t) was computed as shown in Equation (3.2)(ISO, 1974), where b is timber breadth, d is timber depth, l is timber length. Timber recovery rate (R%) was computed using the relationship between log volume (V_L) and volume of the resultant sawn timber (V_T) as shown in Equations (3.3) (ISO, 1974).

$$V_t = \sum(bdl) \quad (3.2)$$

$$R\% = \left({}^{V_t}/_{V_l}\right)100 \quad (3.3)$$

For both chainsaw and bench saw systems, the fuel tanks were filled with known volume of fuel and the volumes recorded at the beginning of each sawing operation. The machine was operated until all the fuel was used up then refuelled with known volume of fuel and the records updated accordingly. At the end of the sawing exercise, the tank was emptied and the balance re-measured to determine the volume of the remaining fuel, which was then deducted from the records. The volume of fuel used was then recorded in litres to the one decimal point. Pit sawing did not involve measurement of fuel since the system is operated manually. After determining the volume of the sawn timber in each case, three pieces of sawn timber from every log sawn using each system were randomly sampled. On each of these pieces, timber thickness (t) was measured in millimetres at the ends and at every 0.5m interval along the length using digital callipers to the nearest one decimal point. This data was used to compute the mean thickness deviation from the pre-set market dimensions. The pieces were then used to obtain smaller samples for wood density tests at 12-15% moisture content and further for timber surface roughness tests.

3.1.2 Data Analysis

The data were analyzed using Microsoft Excel and SPSS software. The effects of (a) wood species and (b) sawing systems, both in isolation and in combination; on (c) log recovery, (d) sawn timber recoveries, (e) fuel consumption rate, (f) sawn timber production rate and (g) timber thickness deviation were determined. Mean comparisons were performed at 95% confidence level.

3.2 Determining the Optimal Design Parameters Using Empirical Approach

Using the results of the comparative performance, the chainsaw system was chosen for optimization for its machine design parameters, to improve on its performance (viz., timber recovery and rough surface quality). The optimization focused on modifying the chainsaw cutter angle from 20-35^{o}and depth gauge clearance from 0.600-0.700mm.The detailed procedures used to modify the chainsaw cutter angle, depth gauge clearance and design and fabrication of the frame are described in the Section 3.2.1.

3.2.1 Modification of Chainsaw System

The part of the chainsaw system that was identified for modification was the chain. The modification targeted to improve the chain cutting properties which influence sawing performance and timber quality. The parameters of the chain that were modified were the cutter angle (α) and depth gauge (d).

a) Modification of the Chain Cutter Angles

At a specified depth gauge, the chain cutter angle was modified from the standard angle of 20 to 35^{o} in steps of 5^{o} using an engineer's protractor and chain angle setting tools as shown in Figure 3.1 and 3.2. Nine (9) new felling chains were purchased from authorized chainsaw retailers in Nairobi together with the appropriate chain maintenance tools (round sharpening file, depth gauge setting tools (Gaugit) and a flat file, an engineer's protractor, a chain cutter angle setting tool and file holder). The angle setting tool and the round file were assembled as presented in Figure 3.1.

Figure 3.1: Chain cutter angle setting tool, round file and file holder assembly.

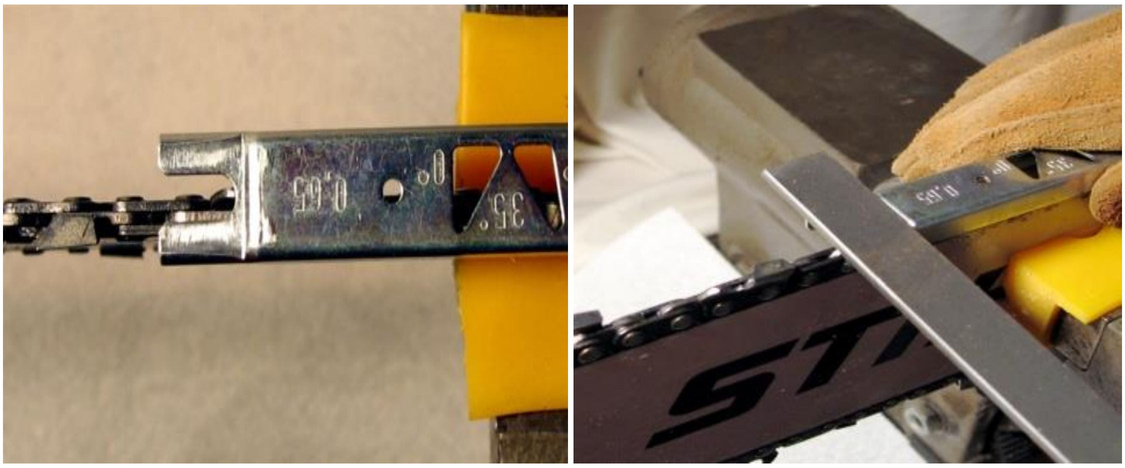
Figure 3.2: Engineer's protractor setting and filling cutter angles.

The chain was attached on the chainsaw machine. With the chain brake engaged, and the chain snugly tensioned, the middle of the bar was clamped in a vice, with the clamping point well away from the bar rails, making sure that the chain was tight enough to prevent the cutters from tilting under the file but loose enough to be moved around the bar by hand. By use of an engineer's protractor (Figure 3.2), the cutter filling angle was adjusted from 20^0 to 25^0 and marked with a sharp marking pen.

A 3.9mm diameter round file was clamped onto a file guide with angle markings to ensure it did not slide out of the witness marks (Figure 3.1). The file guide was placed over the cutter, aligning it with the witness marks set by the protractor. Holding the file with both hands, filing was done from inside the cutter to outside using full strokes and let up on the return strokes. This was repeated until the top plate angle almost conformed to the set angle as shown on the file guide witness marks. Light pressure was then applied until the final angle and adequate sharpness were achieved. After the filling of the cutters in each setting, the metal shavings generated were removed by brushing all accessible surfaces with a stiff brush. These would cause rapid wearing of the chain, sprocket, and bar if not cleaned. The file holder was to guarantee that the angle was accurate and that the profile created by the file was matching that of the service marking, provided that the holder slides on the top plate of each cutter and the adjacent depth gauge. All the cutters were filled on one side of the chain first and then the other side, making sure the right- and left-hand cutters were equal in angles and sharpness. Leather gloves were worn to protect the operator's hands from the razor-sharp cutter edges during the filling.

b) Modification of the Depth Gauge Clearance

Depth gauge setting tools (Gaugit), with different settings was used to set the depth gauge clearance between 0.625-.700mm (Figure 3.3). It was then laid on the chain to cover the cutters with the end notch corresponding to the required depth measurement allowing the depth gauge to protrude out through the notch (Figure 3.3a). For each setting, a flat file was used to file out the depth gauge to the required level (Figure 3.3b). All the depth gauges on one side of the saw were filled before reversing the saw and filing the remaining half of the depth gauges.



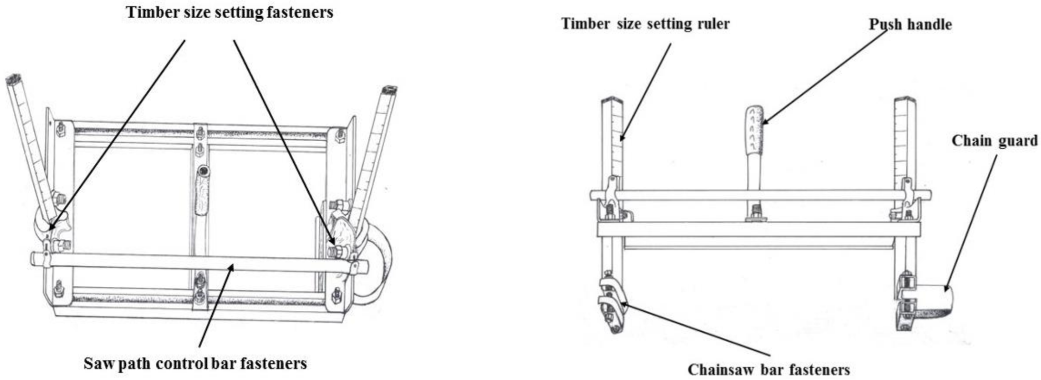
(a) Depth gauge setting (b) Depth gauge filling

Figure 3.3: Procedures for modification of the depth gauges.

To operate with the modified chain, a frame was fabricated to be attached to the chainsaw to control the sawing line. The effects of modification of cutter sharpness angle and depth gauge clearance on sawing speed, fuel consumption and timber dimension variability were then evaluated. Data was then analysed for single and combined effects of these parameters.

c) Design and Fabrication of Chainsaw Frame

A frame, to be attached to the chainsaw was envisaged for effective control of the saw path. A design of a frame attachment to the chainsaw was developed with the help of a draftsman (Figure 3.4). The design and selection of materials were done to balance between strength and weight of the resultant frame (Logosol M7, 2002). Square steel tubes 25mm were purchased and the required parts of the attachment cut to size. The dimensions of the resultant frame were customized to the size of the available chainsaw bar and the diameters of the trees expected to be sawn. A steel fabrication artisan helped in fabricating the frame with close supervision of the scholar in this study. Parts were welded together, taking into consideration the functional properties of each part, size, squareness, strength of joints and flatness consistency. Welded parts were grinded and sanded to smooth surfaces, removing rust and other impurities. Bolts and nuts were used for assembling the parts of the frame that would need to be adjustable during operation. Figure 3.5 shows the frame and chainsaw assembly setup.



(a) Top view (b) Side view

Figure 3.4: Top and side views of the chainsaw frame attachment.

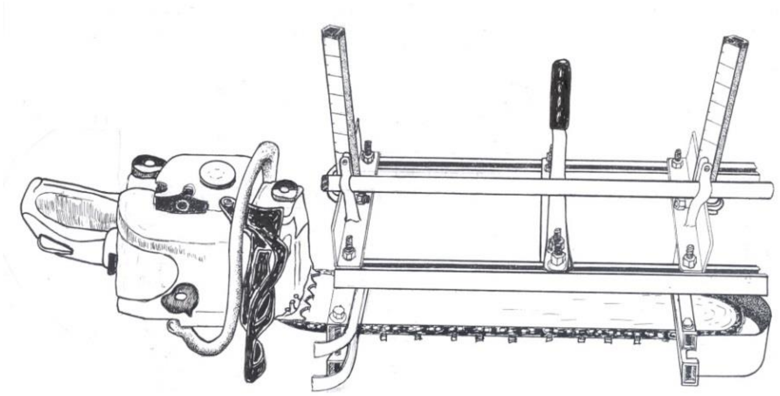


Figure 3.5: Frame and chainsaw assembly setup.

To improve the ergonomic properties of the system, two small but strong racks were constructed using scrap timber on which the log being sawn were placed and fastened using wedges on both sides (Figure 3.6). The design ensured simplicity and light weight to facilitate portability along with the chainsaw assembly.

Figure 3.6: Sawing logs on racks.

3.2.2 Optimization of the Chainsaw System

Twelve square wood beams measuring 150mm wide and 2m long were prepared from 20 years old green *Grevillea robusta* logs sourced from the same farm for optimizing the chainsaw system. The system assembly for sawing the beams is as presented in Figure 3.6. The logs were sawn green. The chainsaw was filled with fuel mixture and chain lubricant to tank capacities and the volume of fuel recorded. The tests involved, first, sawing the beams using the framed chainsaw set at cutter angles of 20 to 35^o in steps of 5^o at a depth gauge clearance of 0.625mm. The frame was adjusted to cut 25mm thick boards over the whole length of the beam. The data collected included sawing speed, fuel consumption and timber dimension variability. Sawing was timed using a stop clock and the sawing speed determined as the ratio between length of beam and time. On the other hand, fuel consumption was measured as the amount used per volume of timber sawn. Finally, for each piece of timber sawn, timber dimension variability was determined by measuring timber thickness from one end to the other at intervals of 0.5m using a calliper (Mitutoyo CD-20APX).For each angle, three replicas of data were recorded. The same process was repeated at depth gauge clearance of 0.650, 0.675 and 0.700mm. A total of 12 data were collected for each angle and depth gauge clearance. Figure 3.7.shows the experimental design used.

Table 3.3: Cutter angle and depth gauge clearance optimization experimental design.

Depth gauge clearance (mm)	Cutter angle (^{o})			
	A_1	A_2	A_3	A_4
D_1	$D_1A_1r_1$	$D_1A_2r_1$	$D_1A_3r_1$	$D_1A_4r_1$
	$D_1A_1r_2$	$D_1A_2r_2$	$D_1A_3r_2$	$D_1A_4r_2$
	$D_1A_1r_3$	$D_1A_2r_3$	$D_1A_3r_3$	$D_1A_4r_3$
D_2	$D_2A_1r_1$	$D_2A_2r_1$	$D_2A_3r_1$	$D_2A_4r_1$
	$D_2A_1r_2$	$D_2A_2r_2$	$D_2A_3r_2$	$D_2A_4r_2$
	$D_2A_1r_3$	$D_2A_2r_3$	$D_2A_3r_3$	$D_2A_4r_3$
D_3	$D_3A_1r_1$	$D_3A_2r_1$	$D_3A_3r_1$	$D_3A_4r_1$
	$D_3A_1r_2$	$D_3A_2r_2$	$D_3A_3r_2$	$D_3A_4r_2$
	$D_3A_1r_3$	$D_3A_2r_3$	$D_3A_3r_3$	$D_3A_4r_3$
D_4	$D_4A_1r_1$	$D_4A_2r_1$	$D_4A_3r_1$	$D_4A_4r_1$
	$D_4A_1r_2$	$D_4A_2r_2$	$D_4A_3r_2$	$D_4A_4r_2$
	$D_4A_1r_3$	$D_4A_2r_3$	$D_4A_3r_3$	$D_4A_4r_3$

r = replica

Graphs relating (i) cutter angle and sawing speed for different depth gauge clearance; (ii) cutter angel and fuel consumption for different depth gauge clearance; and cutter angle and dimension variability were drawn (Excel 2007®) to determine the optimal design parameters of the chain. Models of best fit for the relationships between sawing speed and cutter angle, fuel consumption and cutter angle, and dimensional variability and cutter angle were established for every depth gauge clearance used. The cutter angle and depth gauge clearance combination that gave the highest sawing speed, the lowest fuel consumption and dimensional variability from these models was adopted as the optimum design parameter for the framed chainsaw system.

3.3 Evaluating the Performance of the Optimized Timber Sawing System

3.3.1 Timber Sawing Characteristics

The performance of the framed chainsaw with optimized design parameters was evaluated using three (3) logs each from mature trees of *Eucalyptus saligna*, *Grevillea robusta* and *Prosopis Juliflora*. The chainsaw was filled with fuel mixture and chain lubricant to tank capacities and the volume of fuel recorded. The frame was adjusted to cut 25mm thick boards over 150mm wide and 2m long beam. The data collected included sawing speed, fuel consumption, timber dimension variability and surface roughness. The time taken to saw each beam was recorded for determination of sawing speed. Similarly, the fuel consumption and timber dimension variability were determined as in Section 3.3.1.

After recording data on size deviations on the pieces of sawn timber, each piece was cut into 300mm long pieces and grouped together. Three pieces were randomly sampled from each group, obtaining a total of 81 sample pieces for surface roughness tests using roughness tracing procedures. Before tracing, all specimens were conditioned to 12% equilibrium moisture content (EMC) in a room conditions (25°C and 65% relative humidity (RH)) for 14 days. Surfaces of all the 81 specimens were traced using a commercial stylus tracing Perthometer S6P, (drive unit PRK of Feinprüf GmbH, 37008 Göttingen/Germany). This stylus tracing device is developed for quality control on work pieces with relatively smoother surfaces, such as metals and plastics. It was therefore necessary to calibrate the measurement range for the purpose of this study by elongating the length of the traverse limit (LT) and the vertical limit (VL) of the pickup to 5.6 mm and 250 µm respectively to scan rougher surfaces on timber. This was consistent with similar earlier studies where stylus tracing approach was used for wood surface roughness determination (Funk *et al*, 1992; Richter *et. al*, 1995). On each sample piece of timber, ten measurements were taken systematically all over the surface. Figure 3.7 and 3.8show a photograph and the schematic representation of the equipment respectively, while Table 3.4 shows its measurable characteristics (Richter *et. al*, 1995; Bennett, 1985).

Figure 3.7: Stylus roughness measurement equipment (Model-GmbH/37008).

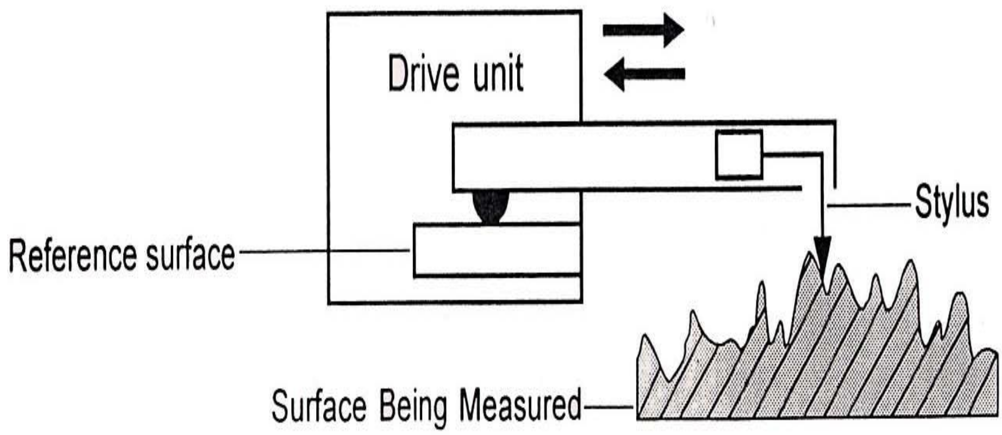


Figure 3.8: Schematic representation of the stylus drive unit.

Table 3.4: Characteristics of the stylus tracing.

Characteristic	Measure
Tracing Direction	Across the grain
Tracing length	60mm
Tracing speed	0.5mm/sec
No. of measured points/traces	6,124
Pickup length	130mm
Stylus measurement range	Max 250 µm
Stylus tip radius	40µm
Force exerted on the surface	130N

Since the number of data points measured per tracing unit on each piece was more than necessary (144 points/sample), the data sets were compressed by selecting every sixth value per tracing unit. The result was a de-trended roughness profile representing 48 mm (reference length) of the tracing length per sample piece, yielding a total of 864 profiles. Three standardized roughness parameters: average roughness (R_a), average roughness depth (R_z), which measures the maximum vertical distances within the reference length and (R_t) (which measures the maximum roughness depth of the valleys), were measured. Two other parameters: peak roughness (P_r) and peak index (Pi) were derived from the obtained data and compared statistically (Ostman, 1983), to find out if all the five parameters were correlated, to warrant a safe use of mean roughness (R_a) in the comparison.

The five roughness parameters selected were compared statistically in a correlation analysis, manifesting a high correlation between all parameters**.** The arithmetic mean (R_a) was therefore safely used in the comparative analysis. Data on size deviation and surface roughness was organized and analyzed separately. A two-way analysis of variance was carried out on all data to determine whether sawing system and wood species significantly influenced the timber size deviation and surface roughness. Differences between the means of independent variables were tested for significance using Tukey's Studentized Range Test at 5% probability level. All statistical analyses were performed with Gen-stat and SPSS software packages.

For each species of wood three (3) replicates were used. The data obtained on timber production and recovery rates, fuel consumption, timber dimension variability and surface roughness were compared with that obtained for freehand chainsaw obtained in Section 3.1. A band saw was also included in this section to serve as control in timber dimensions variability and surface roughness. The choice of a band saw was based on its ability to produce timber with high recovery, uniform dimensions and high surface smoothness.

3.3.2 Economic Performance of the optimized sawing system

The framed chainsaw system with an optimized chain was subjected to economic performance analysis together with the bench saw system, using statistical economic modeling approaches. A statistical model developed for determining the economic viability of timber sawing systems (Samuel *et al.*, 2006) was downloaded online and customized for the prevailing conditions in on-farm timber sawing in Kenya. Input factors relating to on-farm timber sawing were used. They included characteristics of farm trees and their influence on sawing system productivity, timber recovery and economic performance. Resultant marginal returns were obtained and analysed.

Data on the cost of trees and other production inputs and farm gate sawn timber prices was collected from the areas where on-farm timber sawing is a common practice and average values computed and used in the model to relate the performance of the sawing systems to monetary values. Each of the production factors and their respective cost elements were fitted into the customized model using the appropriate equations embedded in the model. The statistical model analysed the factors that affect the performance at primary, secondary and tertiary levels, providing an opportunity to determine how the sawing factors affected the economic performance. Timber recovery was then varied in each case and its effect on these outputs monitored through sensitivity analyses. Various levels of timber recovery were used to model the optimum level at which the sawing system would yield the highest possible economic returns under the prevailing conditions on farms and based on the design characteristics of the sawing system and fuel consumption levels.

a) Tree Characteristics

Data used to characterise on-farm trees comprised of an amalgam of primary measurements, observed and secondary data, collected from sample Counties where wood for this study was obtained. Stem diameter was characterized as small, medium or large and each defined by actual measurements. Stem form was identifies as good, fair or poor accompanied by definitions of each condition. Log and sawn timber volumes as well as timber recovery data obtained in objective 1 and their respective equations were used in the model.

b) Production Cost Components

The total production cost in on-farm timber sawing was represented by two main categories traced for the respective systems; fixed and variable costs. Fixed costs were those that would normally remain unchanged with changes in production levels. They comprised of cost of investment on machinery, depreciation, routine maintenance and interest on capital for those who would borrow resources. Data on the cost of the machines and tools was collected from local machine dealers and machine owners. A straight line depreciation method was used to estimate the residual value of machinery and equipment after every year. Salaries for permanent staff, rent of work space and land rates were not included since operators in on-farm timber sawing are mostly hired casuals and sawing is done on site, where the tree falls.

Variable costs were limited to only directly quantifiable costs and traceable to a particular sawing system and operations related to the system. This included cost of trees, fuel and lubricants. Others like pre-sawing transaction costs (payments for finding and negotiating for tree prices) and sawing labour charges as well as the cost of spare parts, replacement and sharpening of cutting tools were included under this category. Cost for transporting timber from point of processing to the road side and loading on the trucks for transportation to the market was also considered when feasible. The average time used for operations in a day and the practical number of days sawing can take place in a week considering all other associated tasks were included in the model. Total production cost was therefore represented as the sum total of fixed and variable traceable costs as shown in Equation (3.4), in which C_t is the total quantifiable costs, C_f is the quantifiable fixed costs and C_v is the quantifiable variable costs (FAO, 1984).

$$C_t = C_f + C_v \tag{3.4}$$

Other production inputs like fuel and lubricants were computed per hour equivalent of work. Farm gate timber prices in use during the time of data collection, for each species were applied. The expected revenue was represented as the relationship between volume of sawn timber per unit time and the prevailing farm gate timber price.

c) Model Analytical Tools

In addition to the timber production and cost equations outline above, some key economic analytical tools were also applied. In order to maximize Gross Margins (G), the relationship between total expected production costs and total expected revenues weremodelled as expressed in Equation (3.5), where R is total expected revenue from sawn timberand C_t is total expected production cost over time t.

$$\mathrm{G} = \frac{\mathrm{R} - \mathrm{C_t}}{\mathrm{R}} \tag{3.5}$$

The function (G) was further defined by Equation (3.6), where *p* is the species-specific farm gate price of sawn timber, $f(x_{it}, q_{it})$ is the production function and *e* is the production inputs cost vector ($x_i \ldots x_n$).

$$\mathrm{G} = \mathrm{p}f(\mathrm{x_{it}}, \mathrm{q_{it}}) - \sum_1^n \mathrm{e_{it}}\,(\mathrm{x_{it}}) \tag{3.6}$$

The internal rate of return (IRR), Net Present Value (NPV) and Annual Equivalent Value (AEV) were applied in financial investment analysis of the sawing systems. The Net Present Value is the present value of all revenues less the present value of costs, which is expressed as in Equation (3.7), where B_t is Revenues in each year, C_t is total costs in each year, t is operation time in years, T is the life span of the equipment in years and r is the discount rate.

$$\mathrm{NPV} = \sum_{1}^{n}\{(\mathrm{B_t} - \mathrm{C_t})/(1 + \mathrm{r})^{\mathrm{t}}\} \tag{3.7}$$

The annual equivalent value (AEV) combines all costs and benefits into a single sum that is equivalent to all cash flows during an analysis period spread uniformly over the period. It is an annual payment that will pay off the NPV of an asset during its lifetime and is expressed as;

$$\mathrm{AEV} = \mathrm{NPV}\{\mathrm{r}(1 + \mathrm{r})^{\mathrm{t}}\}/\{(1 + \mathrm{r})^{\mathrm{t}} - 1\} \tag{3.8}$$

Sensitivity analysis was then conducted to test the influence of changes in production characteristics on the system economic performance by locating each characteristic in the model and performing a *what-if* analysis on it.

d) Economic Model Assumptions

The model was modified based on some key assumptions. The first assumption was that all financial resources are borrowed. A mean interest rate of 16.5%, which was operational during the time of data collection was used. Next, price of trees and that of sawn timber would remain the same for the entire evaluation period. Further, due to the small quantities of timber sawn on farms, small pickups were assumed to be the most appropriate means of transport for the sawn timber to the market. Finally, trees are felled, prepared and cut to length for sawing by the same crew operating the sawing system but charged separately.

The model was written using the Microsoft Excel spread sheet (Version10) to allow users modify it by overwriting the key factors (marked in red numerals) in the worksheets as shown in Appendix 1. This automatically would update the output displays. To avoid the problem of excel ‘marcos’, which cause difficulties with computer virus protection systems, calculations are contained within the workbook, giving it a large file size. Appendix 1 shows the Excel model frame, without the generated outputs and plots. The Excel-based version is available in soft copy. The results of this modelling process led to the identification of the production factors that governed the profitability of the sawing systems, and which hence the type of improvements that could be needed to give better results.

3.3.3 Ergonomic Characteristics

Ergonomic characteristics of the developed framed chainsaw were analysed to evaluate the risks associated with its operation compared to freehand chainsaw system. Data on working posture, hand-arm vibration (HAV) and noise exposure were analysed using appropriate equipment and methodologies as described below. The tests were carried out with chainsaw operators sawing *Grevillea robusta* logs (20–350-mm diameter) randomly sampled from farms. The trees were felled and crosscut into log lengths of between 2 and 3 meters using a chainsaw. The butt and top diameters and lengths measured to the nearest one decimal point for purpose of computing their volumes. Based on the species density, their individual masses were then computed.

a) Working Posture

The Ovako Working-posture Analysis System (OWAS) was used to evaluate working postures during every stage of operation in each sawing system(Karhu *et al.*, 1981).Posture code combinations based on observation were applied. In each task and for each operator, body postures and the log weight moved were recorded (Figure 3.9) and risk classes computed using the OWAS classification table (Figure 3.10), (Calvo, 2009).Each posture was expressed with a number code (such as code 2162 meaning; bending back, arms under the shoulder and a weight to move between 10 and 20 kg). After recording all postures by the observation of the tasks and work cycles, the data was recorded for use in computing the risk levels associated with each task in a sawing operation.In Figure 3.10, Class 1 in the green cell is connected to normal postures with no discomfort and no effect on health, without any special attention except in some cases. On the other hand, Class 2, the yellow cell refers to postures which must be considered during the first check of the used working methods. Class 3, the orange grey cell means postures which need consideration as soon as possible. Finally, Class 4 are the postures in the red cell that need immediate action.

Figure 3.9: Some of the extreme cases of freehand sawing postures.

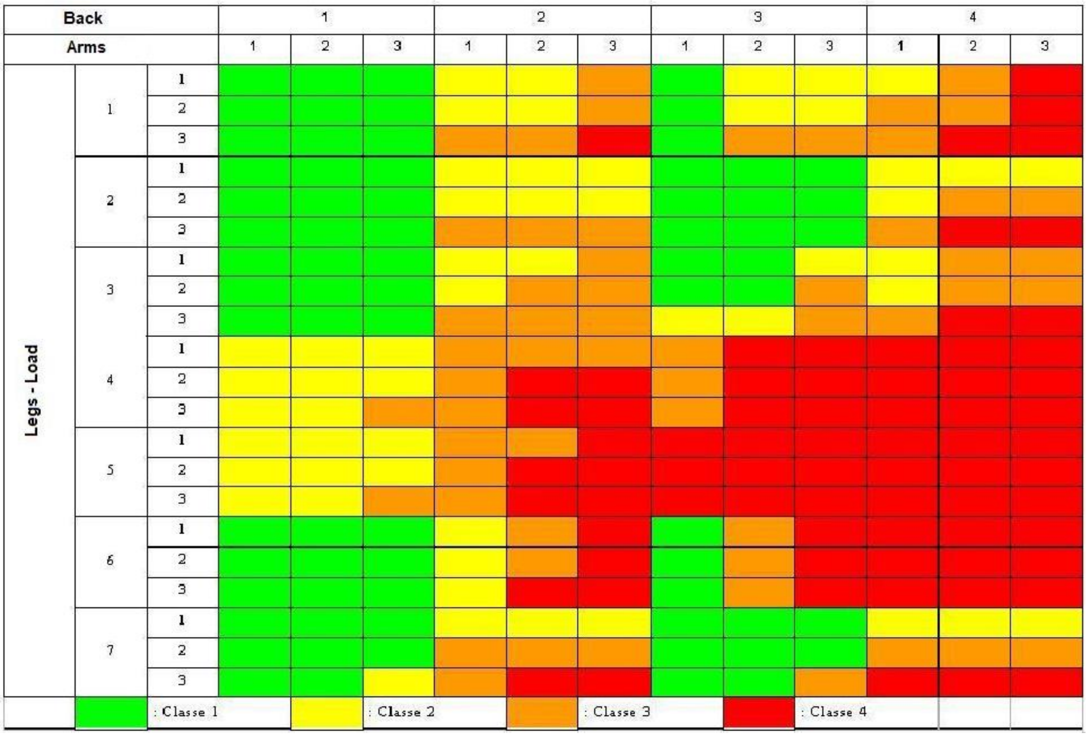


Figure 3.10: Ovako working-posture analysis system (OWAS) classification.

When all codes were determined for a specific task in the operation, the related index risk (I) was calculated using the frequency rate in each OWAS class as in Equation (3.9), where: a, b, c and d are the frequency observation rates in class 1, 2, 3 and 4 respectively.

$$I = [(a * 1) + (b * 2) + (c * 3) + (d * 4)] * 100 \quad (3.9)$$

The index risk ranges between 100 (100% of posture observations in class 1) and 400 (100% of posture observations in class 4). The more the risk factor gets closer to 400, the higher a MSD risk does exist.

b) Exposure to Vibrations

Hand-arm vibration in each task was determined using a vibration meter VB-8213(Figure 3.11). This was attached to the chainsaw handles in freehand and on the frame in framed chainsaw systems respectively, using the magnetic device at the end of the cable. Daily exposure to vibration value {*A(8)*}for each sawing system was then computed, considering both the real time (*T*), when the operator's hands were in contact with the vibrating surface and the acceleration values (a_{hweq}) for the two sawing systems using equation 3.10.

Figure 3.11: Vibration meter.

Figure 3.12: Measuring vibration level.

To obtain the correct exposure at different work phases, the idling condition (chainsaw switches on in the operator's hands, without performing any work), the racing (corresponding to an engine speed of 133% of the speed at maximum engine power, when the operators starts to saw) and the full load condition (sawing phase), were considered, according to the CEN/TR 15350. Vibration level readings were taken in 15s intervals up to the 240ths for each task to permit the calculation of the total acceleration value (a_{hweq}) used to compute the $A_{(8)}$value, as required by the IEC Directive (2002/44), where T_0represents the number of working hours/day, assumed to be equal to 8 hour.

$$A_8 = a_{hweq}\sqrt{T/T_0}\ (\text{ms}^{-2}) \qquad (3.10)$$

c) Exposure to Noise

Alongside vibration, exposure to noise was evaluated by recording noise levels as specified in ISO (2001) and IEC 61672: 2003 taken. A digital sound level meter (Model 407736), which picks, filters and records the noise signal in decibels (dB) was used (Figure 3.12). This was held about 1 meter from the machine to pick noise as close to the operator's ear as possible without interfering with the operator's work (Figure 3.13). Noise level was recorded after every 15 seconds.

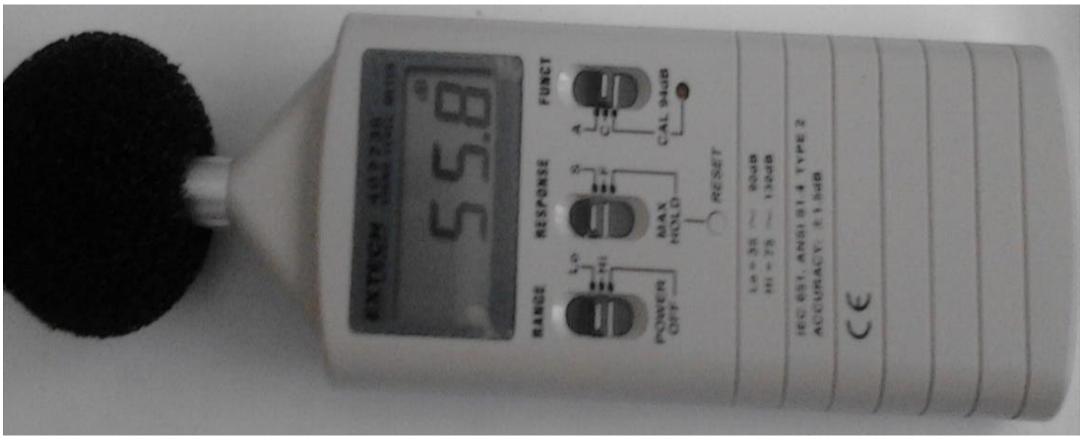


Figure 3.13: Integrated averaging sound level meter.

Figure 3.14: Measuring noise level.

A two-way analysis of variance was carried out on the collected data to determine the effect of sawing system on the level of noise emitted by the machine and the level of vibration. Differences between the means of noise levels were tested for significance using Tukey's Studentized Range Test at 5 percent probability level using Gen-stat software package.

3.3.4 Effects on the Environment

Timber sawing using freehand and framed chainsaw systems was conducted in clean and enclosed spaces. The saw dust produced by each system was trapped and collected in plastic bags and immediately weighed in Kilo-grams. The off cuts were also weighed. The dimensions of the sawn timber were re-determined using digital callipers. This was aimed at determining the amount of wood included in each piece unnecessarily, which represented by oversize. In cases of undersized timber, the pieces were considered as waste since it could not be included in the timber for the market. Using the wood density of the respective species (Table 3.2), the volume of the sawdust and off cuts were computed and expressed as percentages of the input log volume. This constituted the wastes that are deposited to the environment when sawn timber is produced with this system. Determination of the pollutants from the engines was not done in this study due to unavailability of the relevant equipment for analysis.

CHAPTER FOUR
RESULTS AND DISCUSSION

4.1 Comparative Analysis of On-farm Timber Sawing Systems

Analysis of variance for the sawing systems and timber species is shown in Table 4.1.

Table 4.1: Analysis of variance on sawing systems and wood species.

Source	Dependent variable	Sum of squares	df	Mean square	F-value	p-value
Sawing system	Log conversion rate	5.019	2	1.339	76.537	0.000
	Timber production rate	0.429	2	.223	8.723	0.000
	Timber recovery rate	0.312	2	0.719	5.612	0.002
	Fuel consumption	0.168	2	0.169	5.347	0.004
	Dimensional uniformity	0.632	2	0.423	6.104	0.001
Wood species	Log conversion rate	3.224	2	1.331	85.724	0.000
	Timber production rate	0.472	2	0.182	4.700	0.003
	Timber recovery rate	0.561	2	$4.851x10^{-02}$	1.834	0.000
	Fuel consumption	0.243	2	0.110	2.410	0.200*
	Dimensional uniformity	0.152	2	$5.043x10^{-02}$	1.425	0.300*****
Sawing system*Wood species	Log conversion rate	0.973	32	0.202	5.623	0.000
	Timber production rate	0.628	32	0.381	6.132	0.000
	Timber recovery rate	0.491	32	0.264	2.851	0.000
	Fuel consumption	0.485	32	$3.837x10^{-02}$	1.529	0.124*****
	Dimensional uniformity	2.059	32	0.317	8.115	0.000

On the overall, the performance of timber sawing systems differed in a number of efficiency indicators. Timber species also affected the performance of the sawing systems at different levels.

4.1.1 Log Conversion Characteristics

Log conversion rate was affected by both tree species and sawing systems used (Figure 4.1). Within each of the sawing systems, log conversion rate for individual timber species varied significantly ($p=0.000$), with *Eucalyptus saligna* having the highest rate (76.82%) and *Prosopis juliflora* having the lowest (59.23%) for all sawing systems. This was attributed to the stem diameter and form for the individual species, as also reported by Samuel *et al.*, (2006). The most important characteristics that affect log conversion are diameter and form, more particularly tapper. Trees from *Eucalyptus saligna*, which are of large diameter (Table 3.1) and have low taper ratio (near cylindrical form), availing more wood that any of the sawing systems can convert. The near cylindrical shape enables production of more full length timber pieces, unlike logs that have high taper ratio like. Because of the low taper ratio, much of the stem in this wood has the minimum diameter required for conversion into sawn timber. *Grevillea robusta* had the higher taper ration, which reduced the available material in the stem for sawn wood. *Prosopis juliflora* on the other hand, with short and fairly deformed stems of small diameters yielded the lowest volume of wood that can be converted by any of the sawing systems.

Among the sawing systems, chainsaw recovered more logs, with a mean of 75.76% from the available trees of each of the species than bench and pit saw systems. Pit saw system recovered the lowest volume of wood from all the species. This trend was attributes to the type of sawing tools used and the mode of operation of the sawing system. With pit sawing, the log to be sawn must be at least 2.4m long to accommodate one of the operators to stand on one end while sawing the other end. The *Prosopis juliflora* trees used for this study were sourced from a plantation that was planted in the 1980s for drought mitigation in the dry lands. These trees lacked management and grew into bushes with a few dominant trees towering above the rest. The stems were therefore small diameter, crooked and branchy, thus lowering the merchantable stem length and diameter.

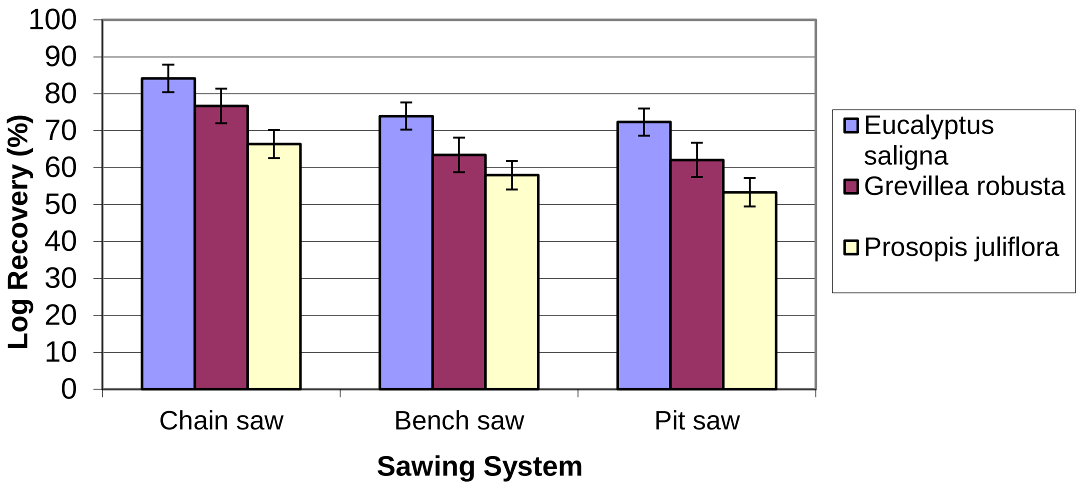


Figure 4.1: Log conversion rate for different sawing systems.

Trees of *Grevillea robusta* from farms possibly lacked management attention due to farmers' limited experience in sivilcultural treatment. This therefore resulted into short merchantable stem lengths. Eucalyptus on the other hand is self-pruning and develops straight and more or less cylindrical stems. This result into longer and straight merchantable logs, which any of the sawing systems could process.

4.1.2 Sawn Timber Recovery

Timber recovery significantly differed among sawing systems (p=0.000). Chainsaw system consistently recorded the lowest mean timber recovery (30%) for all the three species (Figure 4.2). Pit sawing recovered more timber from each species, which was significantly more than the other two systems (p=0.012). When chainsaw system was used to saw the three species, timber recovery for *Eucalyptus saligna* was significantly higher than for *Prosopis juliflora* (p=0.001). However, although the chainsaw system recovered more timber from *Eucalyptus saligna* logs than *Grevillea robusta*, the difference was not significant (p=0.061).

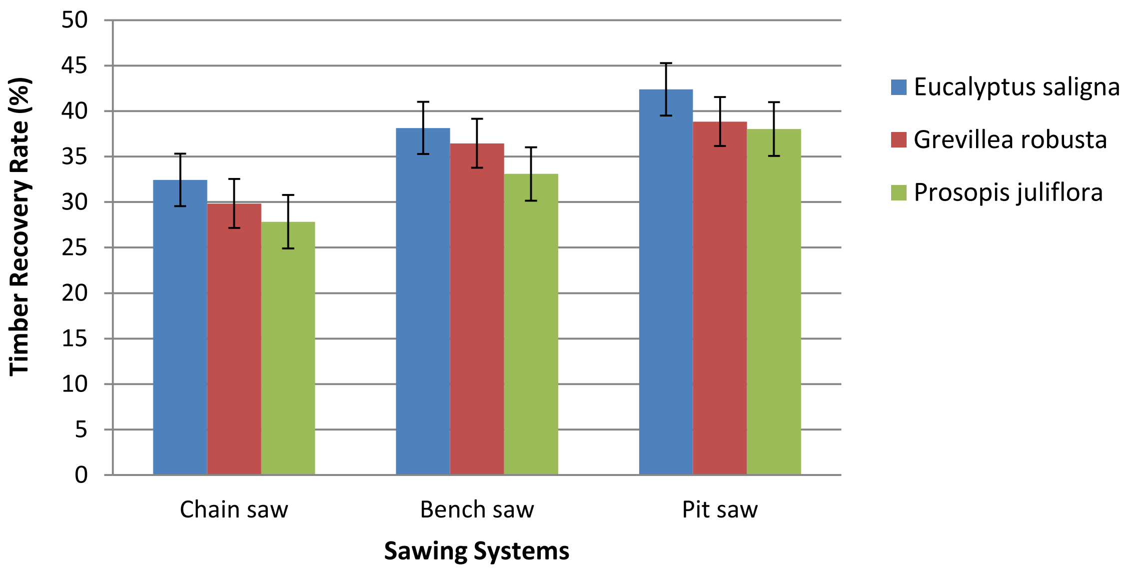


Figure 4.2: Timber recovery for sawing systems.

The results show that among the tree species, *Eucalyptus saligna* recorded the highest mean sawn timber recovery for all the sawing systems, while *Prosopis juliflora* had the lowest timber recoveries. This could be attributed to the log characteristics (diameter and form). These results, however differ from results reported by Grisly (1998), ranging from 22 to 28% for a variety of hard wood species sawn using chainsaws. A similar study, Guillaume *et al*. (2010) reported on-farm recovery rates ranging from 28 to 45% for the same species sawn using small-scale circular saw mills. Such variations may be due to differences in sawyer skills and experience. Studies in Kenya, (Samuel *et. al.*,2006) note that operators' level of skill influenced both recovery and surface quality of sawn timber which is supported by literature (Reineke, 1966).

4.1.3 Timber Production Rate

The volume of sawn timber produced per unit time of system operation varied from system to system. Chainsaw system consistently recorded the highest mean sawn timber production rates per man-hour for all the three species (Figure4.3). Although bench saw system had the highest timber production rate, the system used at least seven labourers unlike chainsaw and pit saw systems which required two operators. On conversion of the production rates per man-hour, chainsaw system performed better for all the species. Among the timber species, *Eucalyptus saligna* produced the highest volume of sawn timber per man-hour for all the sawing systems.

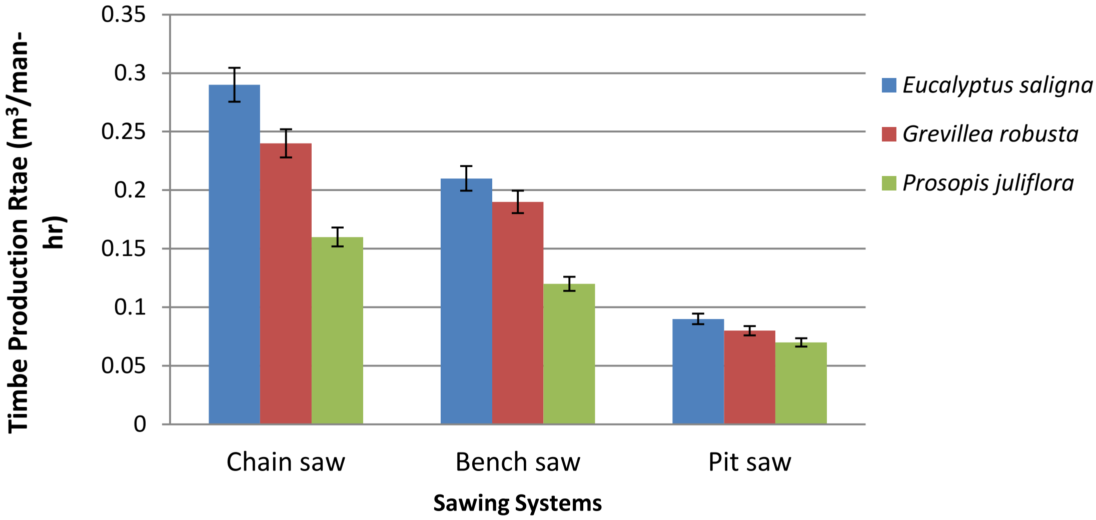


Figure 4.3: Timber production rates for the three sawing systems.

The differences in timber production rate were significant for chain and bench saw systems (p=0.003) but not significant for pit saw system (p=0.0623).

High timber production rate achieved with *Eucalyptus saligna* for all the sawing systems could be attributed to large diameter and good stem form as well as moderate density (640kg/m^3), which makes it relatively easy to saw. Timber production rate for *Grevillea robusta* was lower than *Eucalyptus saligna* despite its lower density (527kg/m^3), possibly due to smaller diameter and poor stem quality. Small diameter logs with poorer stem form associated with *Prosopis juliflora* wood as well as its high density (865kg/m^3) may have been responsible for the low sawn timber production rate. An earlier study in Kenya reported similar trends for *Eucalyptus saligna* and *Grevillea robusta* wood sawn using chainsaw (Samuel *et al*, 2007). In Nigeria, Popoola (2010) reported that timber production rate and recovery increased with increase in log diameter and stem quality for a variety of species. Pit saw recorded the lowest sawn timber production rate for all the three species sawn. This was attributed to the manual operation of the system.

4.1.4 Fuel Consumption

Fuel consumption was analyzed for chain and bench saw systems. Pit saw system was manually operated, therefore did not use fuel. Fuel consumption by chainsaw and bench saw systems differed significantly (p=0.002), for different wood species with bench saw recording higher mean fuel consumption (Figure 4.4). These differences in fuel consumption rate followed a pattern that could be associated with wood density for the respective species. In the two sawing systems, more fuel was consumed when sawing high density wood than when sawing lower density species. The rate of fuel consumption for sawing *Prosopis juliflora* and *Eucalyptus saligna* with chainsaw system however did not differ significantly (p=0.200), although the species densities were significantly different. These results are similar to those reported by Owusu *et al.*, (2011) and De Lasaux *et al.*, (2004). High density wood poses higher resistance to sawing tools and therefore requires more fuel to drive the cutting tools through it.

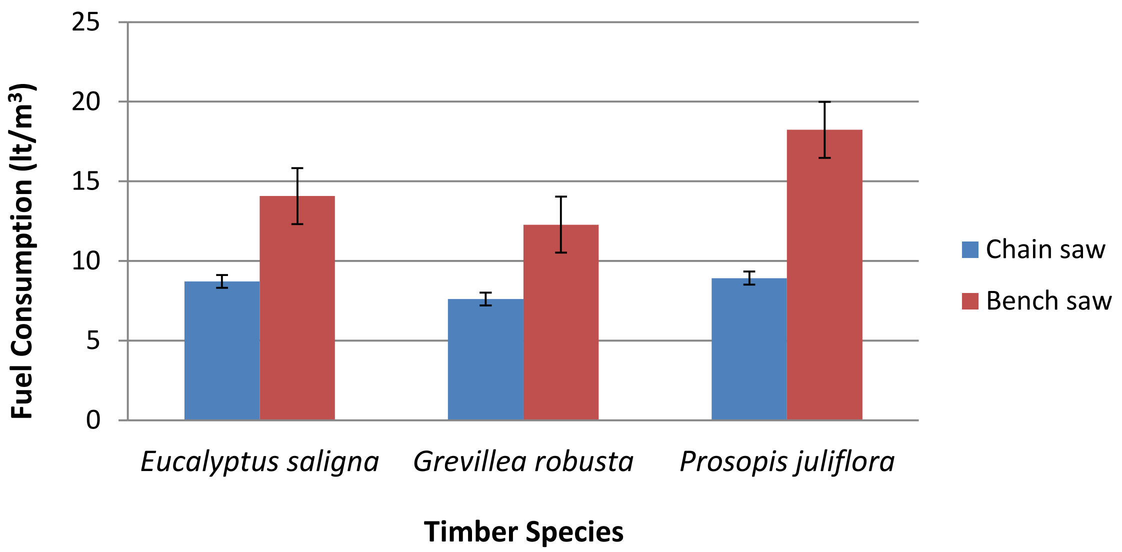


Figure 4.4: Fuel consumption rates for the three sawing systems.

4.1.5 Dimensional Variability

Deviation from the pre-set timber dimensions differed among sawing systems for different wood species (Figure 4.5). On the overall, chainsaw recorded the highest mean timber size deviation. This could be attributed to the mode of operation (freehand), machine vibration due to its engine characteristics (2-stroke), removed depth gauges and machine weight (8kg). Timber size deviations for bench saw could be attributed to inconsistencies due to manual in-feeding of the logs during sawing. Low mean size deviation for pit saw system could be attributed to the mode of operation of the system. Pit saw is operated by two operators, pushing and pulling the saw blade up and down, following lines drawn on the surface of the log being sawn. The operator standing on top of the log directs the saw blade to avoid wavering. Since the operation is manual, the cutting speed is slow and saw vibration is minimal. These reduce possibilities of the saw deviating from the pre-marked cutting line. This improves timber recovery and lowers size deviation.

For all the wood species, *Prosopis juliflora* recorded the highest timber dimensions deviation, which was significantly higher than that for the other species (p=0.000). Although the mean size deviations for *Eucalyptus saligna* and *Grevillea robusta* did not differ significantly, there was a clear trend that timber size deviation increased with wood density for all sawing systems. This could have been a factor of harder wood causing saws to deviate from the sawing line as a result of saw cutters bite into the wood. Other inherent differences in timber properties could also have contributed to variations in timber dimensions from the pre-set sizes. Timber defects such as knots have been shown to interfere with smooth cutting of wood due to the change in density and grain orientation around the knot area (Fehr and Pasiecznik, 2006).

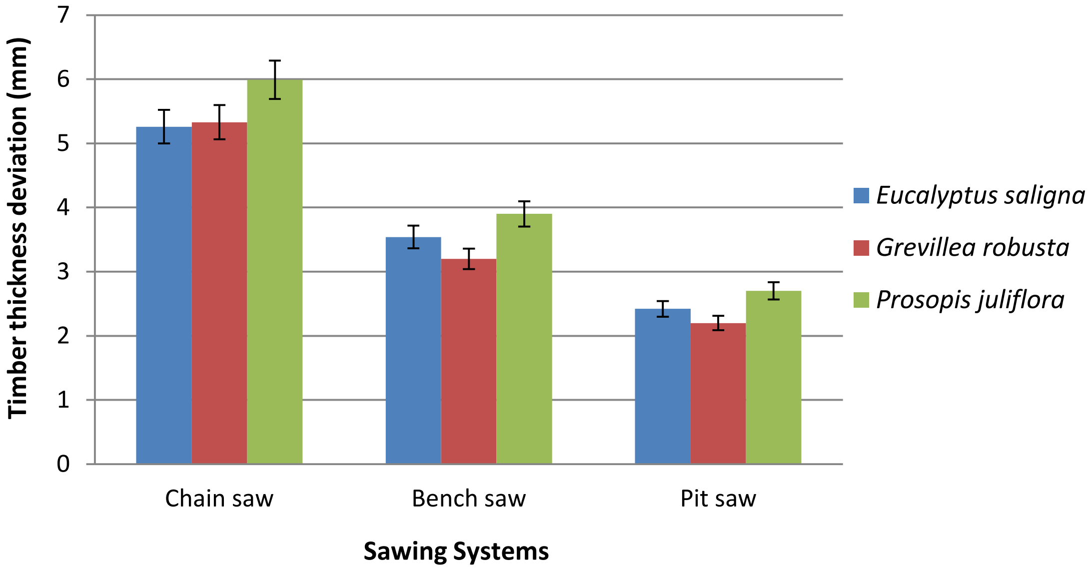


Figure 4.5: Dimensional variability in timber from different sawing systems.

4.2 Determination of the Optimal Design Parameters of Chainsaw System

Figure 4.6 shows the relationship between cutter angle and sawing speed for various depth gauge clearances. The results show that as the cutter angle increases the sawing speed increases in a polynomial manner. The results further show that maximum and minimum sawing speeds are obtained at about angle 25 and 30^{o}, corresponding to depth gauges of 0.650 and 0.700 mm respectively. For this purpose, the respective optimal cutter angle and depth gauge clearance are therefore about 25^{o} and 0.650 mm.

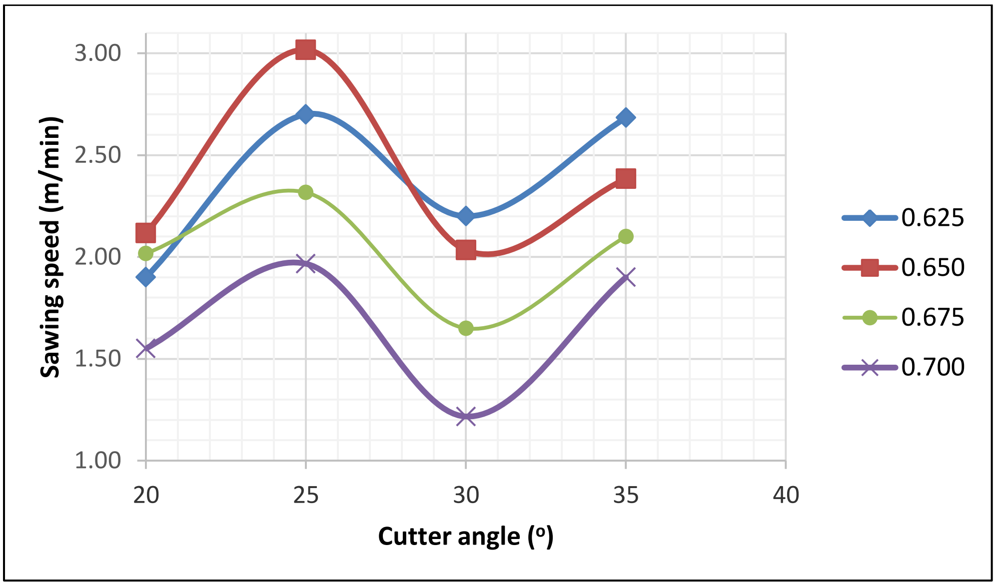


Figure 4.6: Effect of cutter angles and depth gauge clearance on sawing speed for various depth gauges.

Results of the polynomial function of best fit for the relationships between sawing speed (S) and cutter angle (α) are presented in Figure 4.7 and equation (4.1), respectively.

$$S = 0.0043\alpha^3 - 0.3593\alpha^2 + 9.8094\alpha - 84.65 \qquad (4.1)$$

A high coefficient of determination ($R^2 = 0.9313$) was obtained indicating that cutter angle strongly influences sawing speed. From the equation, the maximum and minimum sawing speed are obtained at cutter angles 23.9 and 31.8^o, respectively. These optimal values were obtained using numerical methods since some of the roots were complex. These results imply that the optimal cutter angle is 23.9^o and depth gauge clearance of 0.650 mm. The corresponding sawing speed is 3.26 m/min.

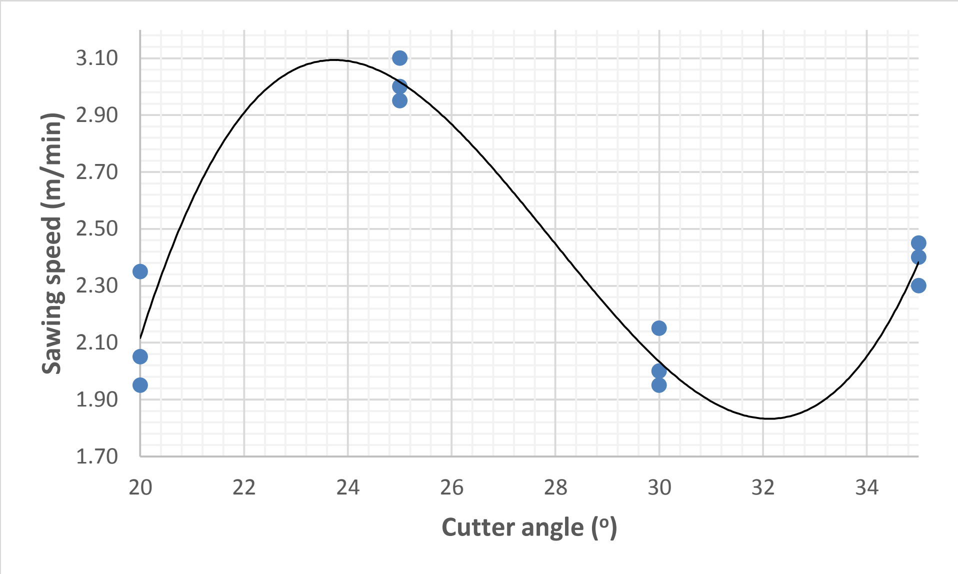


Figure 4.7: Polynomial function relating cutter sawing speed and cutter angle at a depth gauge clearance of 0.650 mm.

Figure 4.8 shows the relationship between cutter angle and fuel consumption for various depth gauge clearances. The results show that as the cutter angle increases the fuel consumption increases in a polynomial manner. The results further show that maximum and minimum fuel consumption are obtained at about angle 25 and 30^{o}, respectively. The minimum fuel consumption corresponds to depth gauges of 0.650 mm for cutter angle of about 25^{o}. Similar results were obtained for timber dimensional variability (Figure 4.9). Although the lowest dimensional variability was obtained at cutter angle of about 25^{o} and depth gauge clearance of 0.700 mm, further analysis of standard deviations showed that depth gauge clearance of 0.650 mm as picked in tests for sawing speed and fuel consumption was more stable. The optimal timber dimensional variability was 1.237 mm at cutter angle and depth gauge clearance of 25^{o} and 0.650 mm, respectively. There was however some unusual trend shown by depth gauge 0.625 and 0.675. Further analysis of optimal level of fuel consumption and timber dimensional variability using polynomial function was not possible with the few data available. These parameters were therefore estimated from the graphs. There would be need therefore to collect more data to complement this study and verify the parameters.

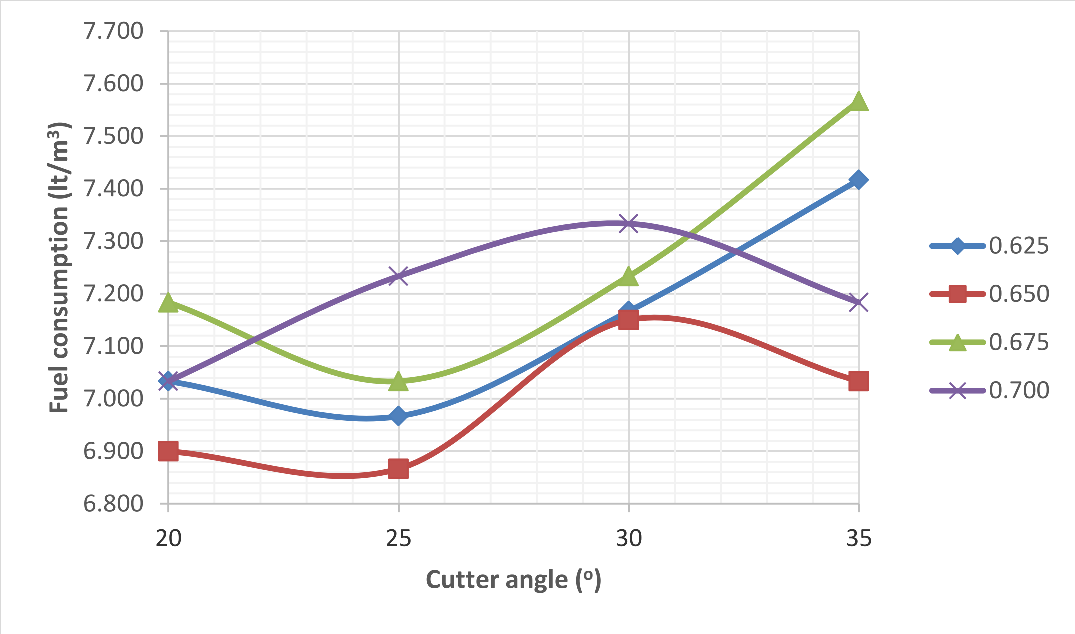


Figure 4.8: Relationship between cutter angle and fuel consumption for various depth gauge clearances.

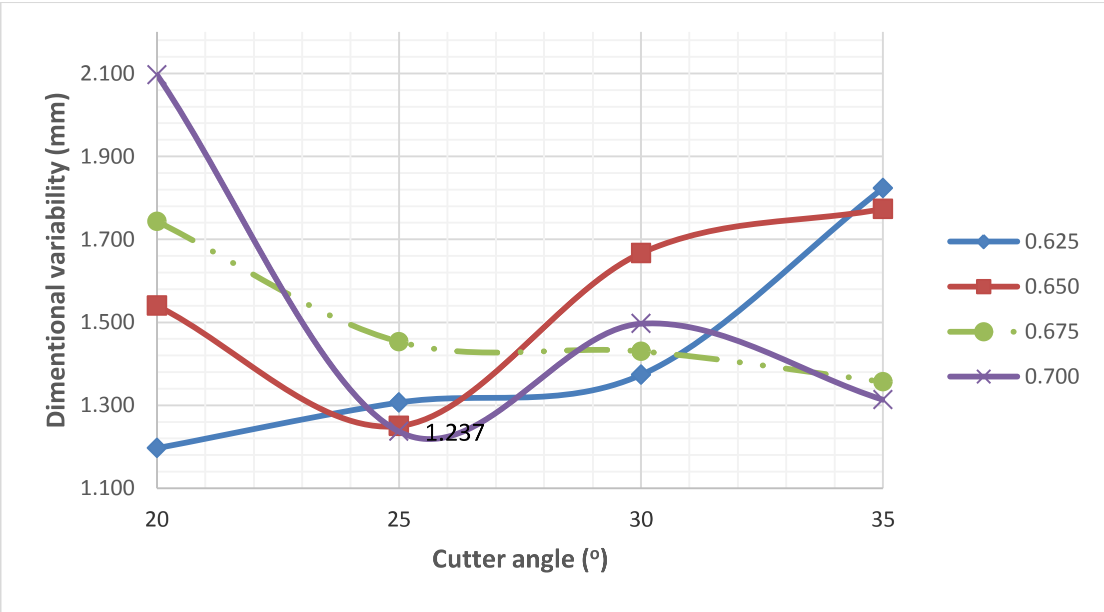


Figure 4.9: Relationship between cutter angle and dimensional variability for various depth gauge clearances.

These results tend to agree with the general working principles of the splitting chainsaw cutters and depth gauges. The cutters on a splitting chain are usually semi-chisel cutters, which have large cutting angle of 25-35^0 (Oregon, 2004). Due to their fairly dull edge, many more cutters can be engaged at a time without adversely slowing the engine. These chains are usually used in framed chain sawing systems. In addition, the depth gauges, which are typically set at lower height than the tip of the corner, ride on the wood and control the depth at which the cutting corner bites into the wood material(Oregon, 2004).This reduces vibrations, keeping the timber surface smooth and dimensions uniform (Pasiecznik, 2006). When the depth gauges are allowed longer than necessary, thus leaving a smaller clearance, they prohibit the cutters from digging into the wood. They only slide on the wood without cutting, which results in fuel usage but no work done. When set too short or totally removed, thus with large clearance as is the case with free hand chain sawing, the cutters can dig too deep into the wood. This however tends to stall the engine and introduce vibrations.

Based on the above principles, when felling chain cutters are used for splitting timber as in the freehand chain sawing with removed depth gauges, the cutters take deep bites into the wood aided by the sharp cutting angle (α). Sawyers therefore use only the tip of the chain bar, thus engaging only a few cutters (Muthike *et al*., 2008). This permits the engine to drive the few engaged cutters to achieve high sawing speed. It however tends to increase vibration, which is the main cause for undesirable noise, variations in timber dimensions and rough timber surface. They also contribute to the increased waste due to the widened saw path (Pasiecznik, 2010).In this study, when the cutter angles were increased and depth gauge clearance regulated (not removed), the biting was limited and therefore the engine power was able to sustain smooth sawing hence increasing sawing speed. Due to the smooth sawing, fuel consumption was reduced. There was also less vibration resulting in smoother timber surface.

At 25^0 angles, the cutters were able to saw with ease, resulting in higher sawing speed, less fuel needed to propel the engine and more uniform timber dimensions.

However, when the angles increase beyond 25^0, the cutters become blunted and unable to effectively slice the wood cells hence slowed the sawing speed (Stihl, 2001). To try to sustain sawing, there was a tendency to force the machine through increasing fuel supply by pressing the fuel button harder. This increased fuel consumption and vibration, hence timber dimensional variability as a result of the cutters inability to saw wood with ease (Muthike *et al*., 2013).

Depth gauge clearance had similar effects to the sawing characteristics. The small clearance on the chain (initial factory set) prevented the cutters from digging into the wood, which like blunt cutters slowed the sawing speed, increased fuel consumption and resulted in high size deviation. Increasing the clearance to 0.650-mm increased sawing speed, decreased fuel consumption and increased timber dimension uniformity. This is associated with the ease of sawing, which is as a result of the cutters having adequate access to bite into the wood (Oregon, 2004). When the depth gauge clearance was increased beyond 0.650-mm, sawing speed decreased. This is as a result of the cutters being able to dig deep into the wood and due to the increased number of cutters in use, more fuel is needed to drive the chain through wood. Like in the scenario where more aggressive cutters are used, higher vibrations are experienced, which result to increased timber size deviation.

4.3 Performance of the Optimized Timber Sawing System

The modified chain sawing system comprised of a framed chainsaw fitted with a felling chain with modified cutter angles to 25^0 and depth gauges to 0.650mm. This was subjected to performance evaluation and the data compared with the earlier data on the performance of freehand chainsaw. Sawing characteristics to include timber production rates, recovery, size variation and surface roughness as well as fuel efficiency were analyzed for three timber species and are discussed in this section.

4.3.1 Timber Sawing Characteristics

a) Timber Production and Fuel Efficiency

Tables 4.2 and 4.3 compare the optimized framed chainsaw and the freehand chainsaw systems in timber production rate and fuel consumption when sawing different timber species. The volume of sawn timber produced per man-hour and fuel consumed by the systems differed for different wood species. On the overall, timber production rate was lower while fuel consumption was higher for framed than for freehand chainsaw for all timber species. This could be attributed to the mode of operation of the framed chainsaw system. Framed chainsaw system cuts with more cutters at a time unlike freehand, which uses the tip of the bar, hence at most two cutters. With more cutters, the engine slows down because of the resistance due to wood hardness and more cutters being engaged. This resistance is increased with increased wood density and hardness and explains why production rate for *Prosopis juliflora* timber was the lowest.

Table 4.2: Timber production rates.

Sawing system	Timber production		
	Eucalyptus saligna	*Grevillea robusta*	*Prosopis juliflora*
Freehand chainsaw	0.21	0.24	0.16
Framed Chain saw	0.18	0.15	0.06

Table 4.3: Fuel consumption rates.

Sawing System	Fuel consumption rate (lts/m^3)		
	Eucalyptus saligna	*Grevillea robusta*	*Prosopis juliflora*
Freehand Chainsaw	8.71	7.61	8.92
Framed Chainsaw	9.98	8.78	12.53

Similarly, with higher resistance to cutting, more fuel is consumed to provide the power needed to keep the machine cutting. These differences in fuel consumption rate follow the same pattern shown by wood density for the respective species (Table 3.1). More fuel was consumed in sawing high density wood than when sawing lower density species. However, the rate of fuel consumption for sawing *Prosopis juliflora* and *Eucalyptus saligna* with freehand chainsaw system did not differ significantly (p=0.034) although the species densities were significantly different. These results show some similarities to those reported by De Lasaux *et al.*, (2004) and Damnyag and Darko, (2009) who observed that high density wood poses higher resistance to sawing tools and therefore requires more fuel to drive the cutting tools through it.

High timber production rate achieved with *Eucalyptus saligna* for all the sawing systems was attributed to large diameter and good stem form as well as moderate density (640Kg/m^3), which makes it relatively easy to saw. Timber production rate for *Grevillea robusta* was lower than *Eucalyptus saligna* despite its lower density (527Kg/m^3). This could have been a factor of log diameter and shape, particularly taper effect in *Grevillea robusta* logs. Small diameter logs with poorer stem form associated with *Prosopis juliflora* wood as well as its high density (865Kg/m^3) were perhaps responsible for the low sawn timber production rate for all the sawing systems. An earlier study in Kenya reported similar trends for *Eucalyptus saligna* and *Grevillea robusta* wood sawn using freehand chainsaw (Samuel *et al*, 2006). In Nigeria, Popoola (2010) reported that timber production rate and recovery increased with increase in log diameter and stem quality for a variety of species.

b) Sawn Timber Recovery

Timber recovery differed from system to system and with wood species. Freehand chainsaw system consistently recorded lower mean timber recovery than framed system for all the three species (Table 4.4). Among the tree species, *Eucalyptus saligna* recorded the highest mean sawn timber recovery for the respective sawing systems, while *Prosopis juliflora* had the lowest timber recoveries. Similar trends were observed when the other sawing systems were used for the respective species.

This could be attributed to the log characteristics (form and diameter size) of the respective species.

Table 4.4: Timber recovery.

Sawing system	Timber recovery (%)		
	Eucalyptus saligna	*Grevillea robusta*	*Prosopis juliflora*
Freehand chainsaw	32.43	29.85	27.84
Framed chain saw	56.45	52.23	47.06

$P<0.05$

These results, though different, show some similarities in range with those reported by other authors. A related study (Guillaume et al., 2010) reported on-farm recovery rates ranging from 28% to 45% for the same species sawn using small-scale circular saw mills, which is within the range reported for bench saw in this study. Small variations may be due to differences in sawyer experience. Samuel *et al* (2007) pointed out that operators' level of skill and experience significantly contributed to variations in both timber recovery and surface quality of sawn timber. It was however observed that high timber recovery from the new framed chainsaw system was consistent for all timber species. This was attributed to the use of the frame. It controlled the sawing line to remain within the chain kerf and not increase as is the case with freehand due to the forward and backward movements during sawing. This therefore reduced the amount of wood material converted to saw dust and others going to slabs and oversized timber.

c) Timber Dimensional variability

In this experiment and the one involving sawn timber surface roughness tests, a band saw was introduced and used as a control. Some of the wood was sawn using the band saw and the resultant timber tested for both size variation and surface roughness. On the overall, freehand chainsaw recorded a mean timber size deviation of ±5.53mm, which was significantly higher than the size deviations recorded for framed chainsaw (±2.44) and band saw (±2.16mm) (Table 4.5). Size deviations on timber sawn using framed chainsaw and band saw systems were not significantly different at p=0.05. This implies that framed chainsaw system produced timber with nearly as good dimensions uniformity as that produced using the band saw.

Table 4.5: Dimensional variability in timber from different sawing systems.

Sawing system	Timber size deviation (mm)			Mean
	Eucalyptus saligna	*Grevillea robusta*	*Prosopis juliflora*	
Freehand chainsaw	5.26	5.33	5.99	5.53
Framed chainsaw	2.42	2.20	2.70	2.44
Band saw	2.14	1.96	2.38	2.16

p=0.05

Timber size deviations differed from species to species for the two sawing systems. *Prosopis juliflora* timber had the highest size deviation from the set dimensions (+/-5.99mm) when sawn using freehand chainsaw which differed significantly from deviations recorded for *Grevillea robusta* (+/-5.33) and *Eucalyptus saligna* (+/-5.26mm) for the same sawing system. The same species produced sawn timber with significantly differing size deviations among the other sawing systems. Size deviation did not differ significantly for the other two species.

Further analysis of the variations of the timber dimensions (Figure 4.10) showed that freehand chainsaw had timber sizes varying widely from one another, with some of the measurements going below the set sizes. Framed chain and band saws had more or less similar variations of sizes with very low deviations compared to the freehand chainsaw. All timber sizes produced by these two sawing systems were higher than the set sizes but fell within small variation limits. The system with the lowest variability is preferred as its timber is more uniform in dimensions.

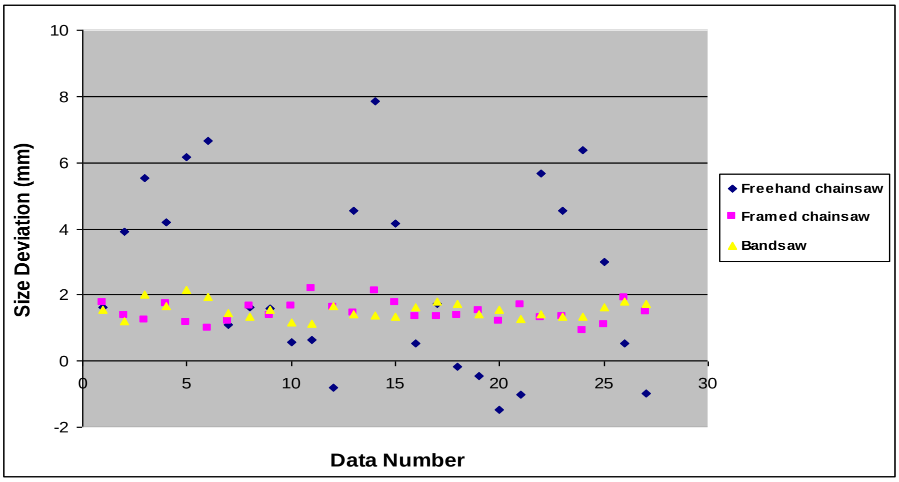


Figure 4.10: Distribution of measured deviations from the set timber sizes for three sawing systems.

d) Roughness in Sawn Timber

Sawn timber surface roughness varied substantially for different sawing systems, among wood species and within the same piece. For ease of evaluation, the three measured and two derived roughness parameters were compared statistically in a correlation analysis manifesting a high correlation between all parameters (Table 4.6).

Table 4.6: Correlation coefficients between roughness parameters.

	R_a	R_z	R_t	P_r	P_i
R_a	-0.932	-	-	-	-
R_z	0.985	-	-	-	-
R_t P_r	0.993	0.984	-	-	-
P_i	0.989	0.978	0.973	-	-
		0.972	0.969	0.991	-

In the table: R_a =mean roughness; R_z =average roughness depth; R_t = maximum roughness depth;P_r = peak roughness; and P_i = peak index (n = 81, p = 0.05)

The highest and most homogeneous coefficients were found for R_a, which represents the arithmetic mean of the absolute values of the profile deviation. Because it is standardized in computation and the parameter is highly relied upon in other studies for roughness characterization (Richter *et al.*, 1995; Östman, 1983), R_a was therefore used in the analysis for ease of quantification and comparison of the timber surface roughness.

(i) Effect of Sawing Systems on Timber Surface Roughness

Mean roughness **(**R_a) for all the profiles scanned in the study was plotted (Figure 4.11). Freehand chainsaw system produced timber with the highest values of R_a. Timber sawn using the framed chainsaw with optimized chain had lower mean roughness very close to that on timber sawn using the band saw (control). The Turkeys mean comparison procedure at 95% confidence proved that mean roughness of timber sawn using freehand (160.41±36.72 µm) was significantly different from the that in timber sawn using framed chain saw (105.34±12.75 µm) and the control (band saw) (95.10± 6.58 µm) with p = 0.00. Timber surfaces for timber sawn using framed chainsaw and band saw systems were however not significantly different (p = 0.13).

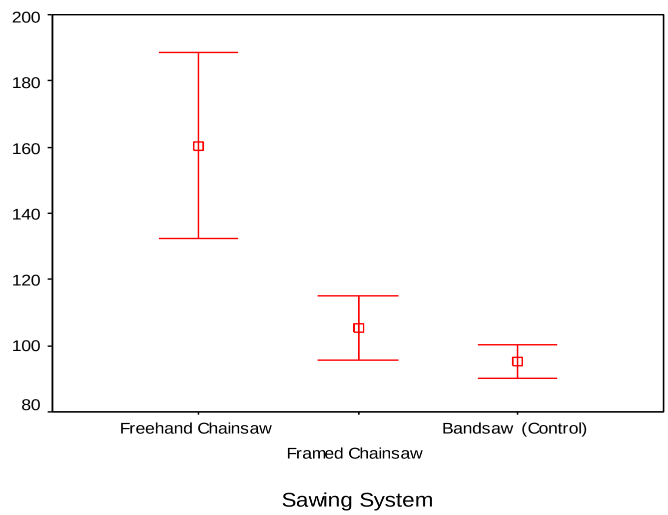


Figure 4.11: Mean values of average roughness (R_a) for three sawing systems.

It is also observed that freehand chainsaw system produced timber with both high roughness values (R_a) as well as higher standard deviations for all the wood species than both framed chainsaw and the control (band saw). This implies that timber sawn using this system varied in surface roughness more than that sawn using framed chainsaw and band saw. The standard deviation was lower for smoother samples where timber surfaces from framed chainsaw and band saw (control) systems showed a better homogeneity than timber surfaces from freehand chainsaw system.

(ii) Effect of Wood Species on Sawn Timber Surface Roughness

The effects of wood species on surface roughness are shown in Figure 4.12, where R_a values for the three species are depicted. There was a difference between surface roughness (R_a) between *Prosopis juliflora* and both *Eucalyptus saligna* and *Grevillea robusta* timber. The standard deviation was lower for smoother samples where timber surfaces from *Eucalyptus saligna* and *Grevillea robusta* timber indicated a better homogeneity than surfaces of *Prosopis juliflora* timber. Turkeys mean comparison procedure at 95% confidence proved that mean roughness of timber from *Prosopis juliflora* timber (139.90±47.25µm) was significantly different from that from Eucalyptus (115.69±29.02 µm) (p= 0.001) and (105.27±23.35µm) (p= 0.000). Surface roughness for timber from *Eucalyptus saligna* and *Grevillea robusta* did not differ significantly (p= 0.124).

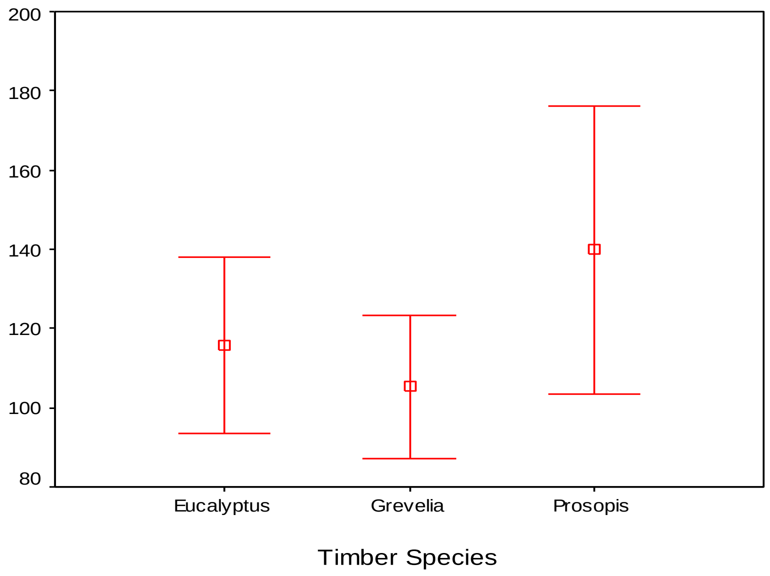


Figure 4.12: Effect of wood species on sawn timber morphology.

(iii) Combined Effect of Sawing Systems and Wood Species on Timber Surface Roughness

The combined effect of sawing systems and wood species on sawn timber surface roughness is shown in Table 4.7 and Figure 4.13. The highest mean roughness was recorded in Prosopis timber sawn using Freehand chainsaw system (201.00 ±20.08 µm), which differed significantly from all the other combinations ($p = 0.001$). The rougher surfaces, mainly resulting from the use of freehand chainsaw system were characterized by a much higher variability within the individual timber species as well as among the different species. Grevillea timber sawn using framed chainsaw system had significantly the lowest mean roughness (88.87±1.12 µm) when compared with all the other combinations ($p = 0.000$). This roughness did not however differ from that of same species sawn using band saw system.

Table 4.7: Effect of sawing systems and wood species of timber morphology.

Sawing System → Wood Species ↓	FreeHand Chainsaw	Framed Chainsaw	Band saw (control)
Eucalyptus saligna	144.27± 35.52	111.70± 4.51	91.10± 1.37
Grevillea robusta	135.97± 6.30	88.87±1.12	90.97±3.91
Prosopis juliflora	201.00±20.08	115.47±2.75	103.23±2.65

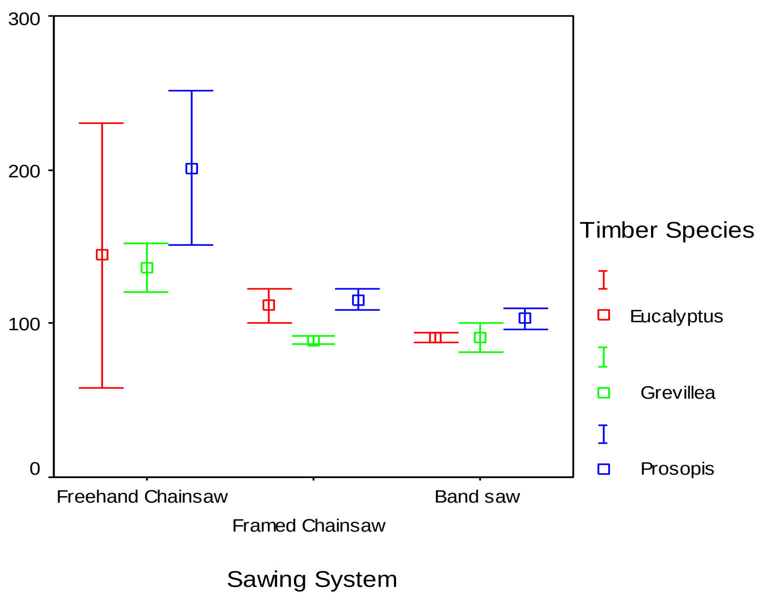


Figure 4.13: Effect of sawing systems and timber species on sawn timber surface roughness.

From the results presented, timber size uniformity can be shown to be a factor of both the sawing system design characteristics and wood species properties. Freehand chainsaw produces timber with inconsistent dimensions and high roughness values.

This could be attributed to a combination of various factors: During sawing, the operator has to hold the total weight of the machine to keep it in sawing position. This in addition to the back and forth mode of operation of the system and its inherent vibration characteristics could make it difficult for the operator to keep the chain cutting consistently on a straight line. Similarly, the use of only a few cutters (only at the tip of the chain bar) with removed depth gauges increases the cutter aggressiveness and therefore vibration. These characteristics make it more difficult for the operator to control the machine and contribute to both inconsistent timber dimensions and increases surface roughness.

In framed chainsaw system, when the frame is attached to the chainsaw, it rests on the log being sawn, taking up the weight of the machine and controlling the chain to cut consistently on the pre-set sawing line. The timber dimensions adjustment bar on the frame is used to set the required timber size, acting in the same way as the machine fence used in the band saw (control). Modification of the felling chain cutters decreases cutter angles as well as controlling the depth gauge clearance instead of removing the depth gauges all together. These two make the cutters less aggressive and therefore stabilize the chain rate of sawing, reducing vibration and therefore the variations on the timber size and surface roughness.

There was a clear trend showing that dimensional variability and surface roughness increased with wood density for all sawing systems. This was pronounced especially for harder species being sawn using freehand chainsaw, which could have been a factor of harder wood resisting the cutters as they bite into the wood and causing cutters to vibrate and deviate from the set sawing line (Fehr and Pasiecznik, 2006). Although similar resistance is experienced when framed chain and the band saws are used, the frame is able to hold the chain more firmly on a straight sawing line while the optimized cutters control the vibration of the chain in the wood, thus resulting in smoother timber surface.

4.3.2 Economic Evaluation of the Optimized Timber Sawing Systems

On-farm timber production costs consist of all the costs incurred in the production of sawn timber. They include cost of trees, fuel and lubricants as well as the initial investment on machinery, maintenance and depreciation of the equipment. In this study, depreciation of machinery was included to enable determination of payback period for the equipment and associated accessories.

a) Cost of Equipment and Depreciation

Table 4.8 shows the purchase and residual values after depreciation of the equipment used in on-farm timber sawing based on fixed declining balance. Results showed that the life-span of a new chainsaw was still shorter than that of the used fabricated frame. With good maintenance, chainsaw and frame were modeled to serve for over ten years while the new chainsaw could only serve for 6 years.

Table 4.8: Sawing machinery valuations, longevity and depreciation.

Valuation and depreciation on capital (Ksh)		Frame Locally fabricated	Chain saw (Husqvarna 272)
Purchase Value		13,570	62,220
Lifetime (years)		6	6
Residual value (estimated)		1,615	32,950
Depreciation (Fixed declining balance) Ksh/ per year	Year 1	11,030	20,145
	Year 2	9,825	13,600
	Year 3	7,215	9,180
	Year 4	5,200	6,205
	Year 5	3,695	4,250
	Year 6	1,615	2,890
	Year 7	1,045	

b) Economic Analysis of Sawing System Based on Log Characteristics and Timber Recovery

Table 4.9 shows the modeled returns when the systems saw medium diameter logs like those commonly available on farms. These returns were modeled with the systems set to operate at timber recovery of 56%. Framed Chainsaw system was modeled to give almost higher returns per cubic meter of sawn timber as the freehand chainsaw system. These differences could be attributed to the characteristic differences in timber recovery for the two systems. Also due to better timber surface and more uniform dimensions, framed chain sawing produced more salable timber than freehand chainsaw system. The results indicated that it was more profitable investing money in framed chain sawing, which gave gross margins of 107.1 per unit currency invested and Ksh. 23581.55 per cubic meters of sawn timber compared to free hand chain sawing with an investment return of only 79.05 per unit currency and a margin of about Ksh.16, 983.67.Further analysis on the modeled relationship between timber recovery and gross margins in the long term indicated that gross margins are directly proportional to timber recovery for both sawing systems.

Figure 4.14 present the relationship between long term gross margins and timber recovery for both the bench saw and chain saw systems. The highest gross margins of (Ksh. 9390.18 and 14890.55) were obtained for saw bench and chain saw systems, respectively, at timber recovery range of 60-64%. Chain sawing was modeled to perform better than bench sawing for all timber recoveries. Gross margins dropped as timber recovery decreased and saw bench recorded no profit with recoveries below 25% and it made losses when recoveries were set at below this level. Chain saw made higher gross margins than saw bench in all timber recoveries above 20%, but it made losses at recoveries below this level.

Table 4.9: One year returns from framed chainsaw and freehand chainsaw.

	Returns (Ksh)	
Framed Chainsaw	Per unit of capital invested	Per m^3 of sawn timber
Total first year costs	l96.05	16,170.40
Gross income	303.15	39,751.95
Gross margin	107.10	23,581.55
Freehand Chainsaw System		
Tota costs	109.65	22,768.28
Gross income	190.40	39,751.95
Gross margin	80.75	16, 983.67

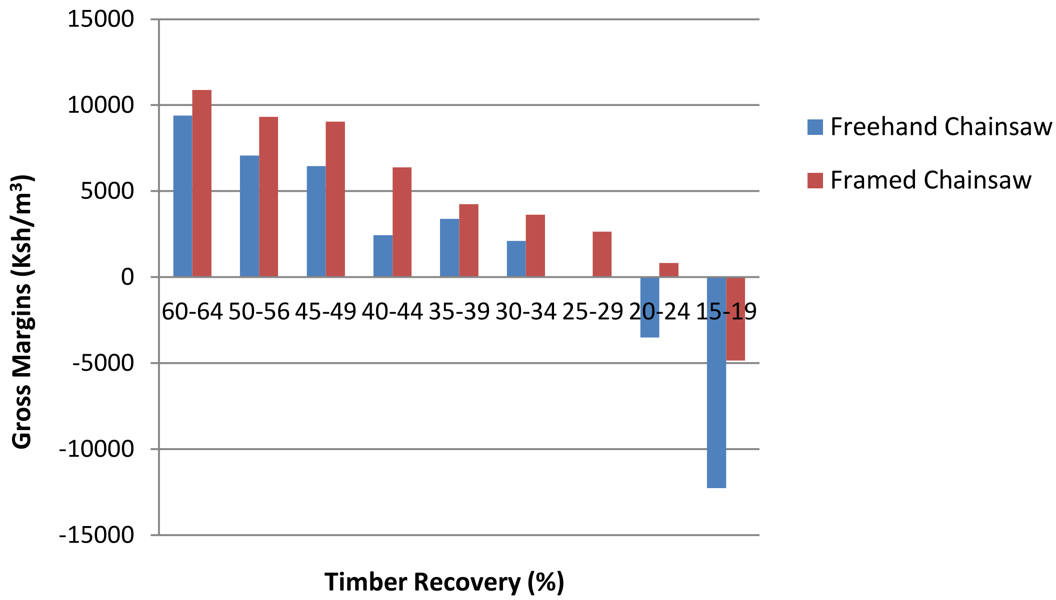


Figure 4.14: Gross margins for freehand and framed chainsaws

c) Economic Analysis of Sawing Systems Based on Pay Back Period

When the performance of the sawing systems was evaluated based on the break-even price of timber and payback period, owing to the farm gate timber prices, the results showed that all the employed factors had significant influence on the break-even point for each sawing system (Table 4.10). The modeled margins per cubic metre of sawn timber shows the framed chainsaw system performing better than freehand chainsaw system the difference being due to the higher timber recovery by the framed chainsaw system.

When revenue data was analyzed based on break-even points, governed by a market prices of Kshs 8358.90/m^3 for *Grevillea robusta* timber, framed chainsaw system reached break even at a price of Kshs 7,085while the same timber sawn with freehand chainsaw would sell at Ksh. 8187 per cubic meter.

Table 4.10: Economic analysis of the sawing systems based on breakeven points.

Framed Chainsaw	Performance
Breakeven farm gate timber price (Ksh/m^3)	7,085.25
Breakeven sawing and selling timber (days)	14
Payback period on sawing and selling timber (days)	101
Freehand Chainsaw	Performance
Breakeven Farm gate timber price (Ksh/m^3)	8,187.40
Breakeven sawing and selling timber (days)	41
Payback period on equipment (days)	197

With such returns, operating a combined business of sawing and selling timber indicates that 14 days would be required to saw timber to cover all the costs for framed chainsaw system, while the freehand chainsaw system would require 41 days. Under such circumstances, framed chain saw system would payback all the costs in a period of only 101 days compared to the equivalent of 197 days required for repayment of the freehand chainsaw system.

4.3.3 Ergonomic Characteristics of Framed Chain Sawing System

a) Working Posture

Timber sawing on farms is usually done at the felling site. Because of the different operations from felling to sawing of timber, the operators in both freehand and framed chainsaw systems are exposed to a variety of working postures, which were each analyzed separately using the OWAS classification system (see Section 3.5.2; Figure 3.10). When sawing with the old freehand chainsaw system, logs had to be lifted and stacked on the sawing position. During log lifting, operators worked with bend or twisted back, standing with the weight on one leg or with the knees bent, the arms below shoulder level and moved weights more than 20 kg. This resulted to a high frequent code of 4173, which fell in class 4 (Figure 4.16). During freehand chain sawing, with the log lying on the floor or supported by small logs, the operator was standing with the body weight on one or two legs, twisting or bending the back and the arms always under shoulder height holding a 8kg chainsaw (Figure 4.15). The applicable OWAS code for this task realization was 4131 (class 4).Overall results on freehand chainsaw operations show that the presence of posture codes in class 3 and 4 for freehand chainsaw operators had factor frequencies of 52 and 81% during sawing, while manual log stacking had factor frequency of 58%. This means that when sawing with freehand chainsaw, the sawing operations expose the operators to higher level of poor working posture than all other operations. These high factor frequencies underline the severe risk for the operators to develop MSD when operating freehand chainsaw system.

Figure 4.15: Freehand chains sawing with bend back.

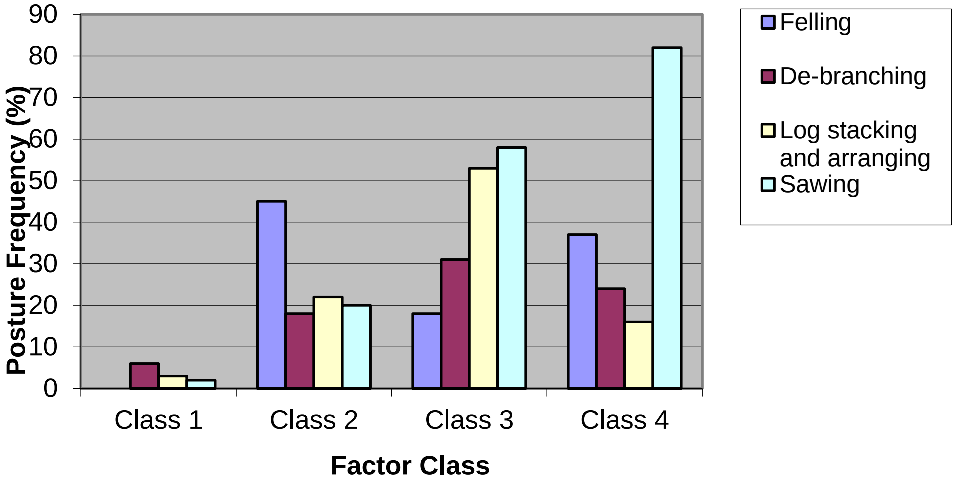


Figure 4.16: Working posture analysis for freehand chain sawing system.

In sawing with framed chainsaw, logs were lifted and placed on the sawing table. This involved two operators lifting one log each time, from the ground. For this operation, they were working with the straight back and bent knees at the beginning of the movement, to finish with straight back and with the weight over the 2 legs. These movement characteristics resulted to code 2143, which falls in class 3 (Figure 4.17). Lifting of the heavy logs sometimes beyond 20Kg resulted to code 3251, which falls in class 4 with a high frequency of 81%. Timber sawing with framed chainsaw involved the sawyer working with straight back, with body weight over the two legs and arms below shoulders and slightly bent. This results to code 2123, (class 2). These results indicate that during timber sawing with framed chain sawing system, although during manual log extraction, the worst average index risk is in the manual log lifting (factor frequencies of 69 and 81% of class 3 and 4 respectively, the sawyers are only exposed to this risk for a short time during the lifting. During the sawing operation which takes longer time, the class 1 and 2 are predominant (factor frequencies of 59 and 42%, respectively). The operator is therefore exposed to lesser risks when using framed chainsaw than freehand chainsaw system.

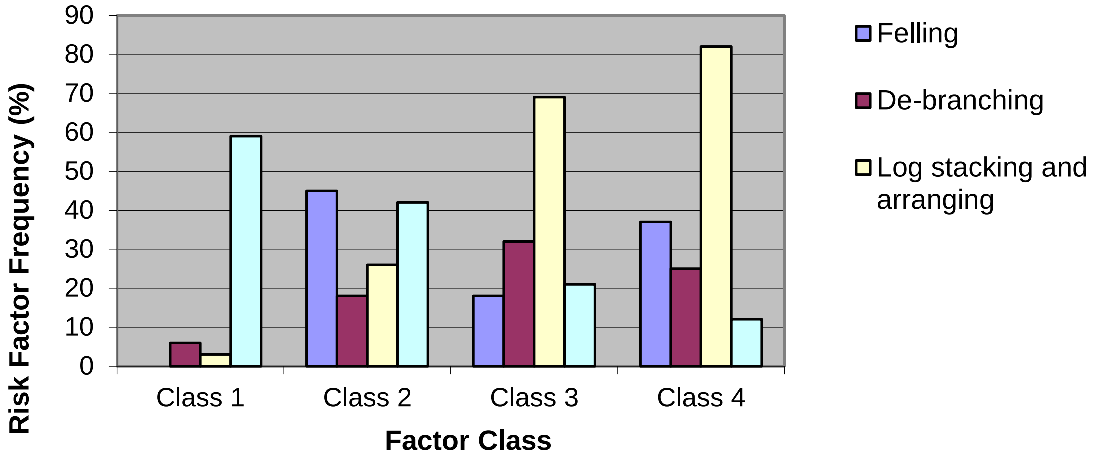


Figure 4.17: Working posture analysis for framed chainsaw.

b) Vibration Levels of the Framed Chain Sawing System

Alongside risks associated with body posture, exposure to HAV transmitted from the chainsaws to the operator's hand-arm system is of critical importance. Results indicated that vibration increased with time but at varying magnitudes during the operations of freehand chainsaw (Figure 4.18). These increasing oscillations could be attributed to the varying levels of acceleration the operator needed to apply when sawing repeatedly as he moves the saw forth and backwards. Table 4.10 shows the maximum computed HAV daily exposure values for both sawing systems.

Table 4.10: Maximum HAV values for freehand and framed chain saw systems.

Sawing System	Hand/handle	Daily A(8) value (m/s^2)
Freehand chainsaw	Accelerator hand	6.8
	Handle hand	5.2
Framed chainsaw	Accelerator hand	4.3
	Handle hand	2.7

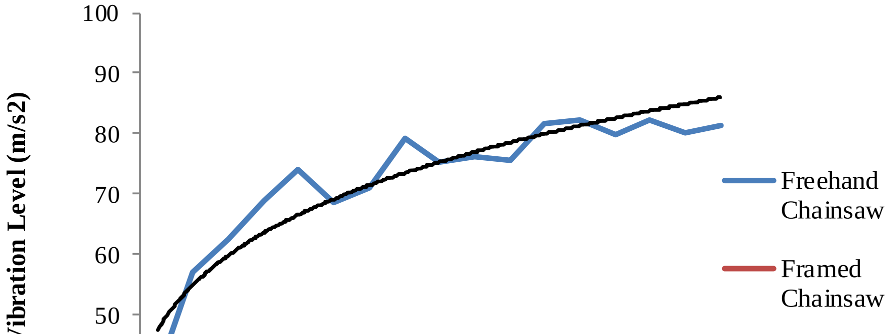


Figure 4.18: Vibration levels for freehand and framed chainsaw systems.

The daily exposure HAV levels were significantly higher for the accelerator and handle hands in freehand chainsaw system than for framed chainsaw system ($p=0.034$ and 0.041 respectively). The maximum HAV value for the freehand chain sawing system was way above the daily exposure action value, as stated by the 2002/44/EC Directive. These are likely to cause risks to the operators. Vibrations emitted by the framed chainsaw were at almost the same level at all the time of operation at a maximum that was below the daily exposure action value.

c) Noise Levels for the Framed Chain Sawing System

Similar to vibration, freehand chainsaw operated at higher noise levels than the framed chainsaw (Figure 4.19). Although both systems displayed variations in noise levels, the peak for freehand chainsaw was way higher than that for framed chainsaw, which was almost constant. The reduction in noise when the chainsaw is attached to the frame can be attributed to the control effect of the frame on the chain. When controlled to cut on a straight line, there is less vibration and therefore less noise. This then translates to the more uniform timber dimensions, smoother surfaces as well as reduced saw dust.

Although it is not very easy to provide absolute measures to eliminate risks in forestry operations like felling and manual log extraction and stacking, the high risk levels obtained for freehand chain sawing in this work are mainly due the machinery type (chainsaw) and the mode of operation. Sawing with the tip of the chainsaw bar, engaging a few cutters with too sharp angles and large depth gauge clearance. This increases vibration as the cutters try to jump out due to increased resistance as they come into contact with the wood. The operator has to keep the tip of the chainsaw bar pressed down to keep cutting against the kickback phenomenon. This increases the operators' exposure to vibration and noise. In uncontrolled operations as is the case in the field operations, difficult environmental situation of operation sites (ground slope, irregular ground with the presence of tree stumps and branches) and to some extent lack of proper personal protective gear significantly increase the risks associated with these exposures.

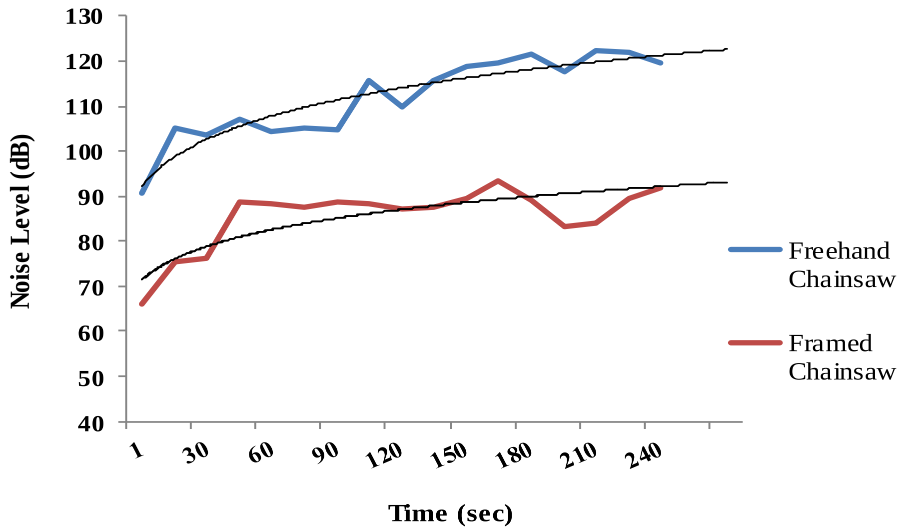
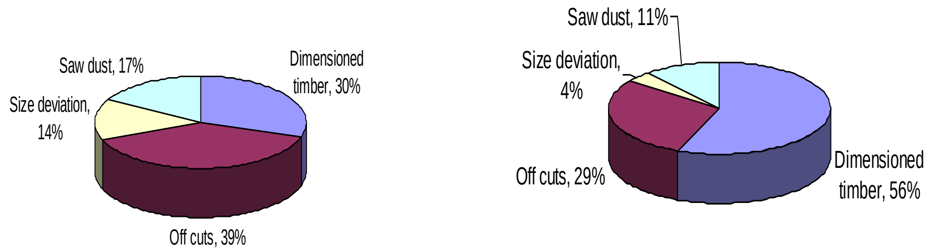


Figure 4.19: Noise levels for freehand and framed chainsaw systems.

The frame absorbs some of the vibrations emitted by the chain through restraining the cutting chain within the wood. This therefore reduces the vibrations and subsequently the noise levels. By using the framed system together with the sawing bench, the OWAS frequencies are significantly lowered and the daily exposure levels $\{A_{(8)}\}$ reduced too. Similarly, the mental demands on the operator, due to the care he has to exercise while handling freehand chain sawing is higher and of more importance than the mechanical work demands. This causes high mental fatigue and faster loss of concentration. The use of the frame makes the system friendlier and less demanding in terms of careful operation.

4.3.4 Effects of On-farm Timber Processing Systems on the Environment

The two chainsaw systems produced sawn timber at different recovery levels and respectively different levels of each by-product. The amount of saw dust, which was the main focus of this experiment, differed significantly between the two sawing systems. While the freehand chainsaw produced 17% of saw dust, the framed chainsaw system reduced it to 11% (Figure 4.20). Reduction of saw dust is attributed to the controlled sawing kerf, which in effect reduces the amount of wood material that is reduced to saw dust. This translates to reduced effects on the environment in two ways. Firstly, less saw dust in the environment reduces the disposal demand for the same. Secondly, the wood material that could have gone into waste as saw dust is translated into dimensional timber. Fewer trees are therefore needed to satisfy the demand for sawn timber.



(a) Freehand chainsaw (b) Framed chainsaw

Figure 4.20: Waste distribution for freehand and framed chains saw systems.

This is a key contribution of the framed chainsaw system in addition to the ergonomic and operational safety this system offers. Similarly, reduction of the other by-products (off cuts) also contribute to reduced negative effects to the environment particularly in areas where these off cuts are not highly utilized, may be due to availability of fuel wood or other sources of fuel. This makes the framed chainsaw a choice system for the on-farm timber process in Kenya in these times of greater need for raising forest cover to over 10% by 2030.

CHAPTER FIVE
CONCLUSIONS AND RECOMENDETIONS

5.1 Conclusions

This study applied empirical approach to determine optimal design parameters (viz., chain saw cutter angle and depth gauge clearance) of the chainsaw system for eco-efficient timber sawing on farms. The performances of three on-farm timber sawing systems (viz., bench, chain and pit saws) were compared. The study established that:

1. The three sawing systems used for sawing timber on farms in Kenya (viz., bench, chain and pit saws) differ significantly in their performance. Their performance is also significantly influenced by the timber species sawn due to inherent timber characteristics. Chainsaw system, though recovering less sawn timber, was more economical than the other systems due to its portability particularly for small diameter logs and in situations where trees are few and scattered as in the case on farms. The low timber recovery and non-uniform timber sizes, associated with this sawing system make it a poor performer, especially when timber is desired for specialized applications. Despite a relatively higher timber recovery rate, pit sawing was the most uneconomical amongst the three timber sawing systems.
2. An empirical approach can be adequately used in determining the optimal design parameters for the chainsaw (i.e., cutter angle as $25^{o}$and depth gauge clearance as 0.650mm). These parameters make felling chains more appropriate for sawing timber with the framed chainsaw system. It was further demonstrated in this study that the sawing system has different effects on sawn timber surface morphology due to their differences in design parameters. The design of the cutting tools and timber dimension control mechanisms (frame) used on the sawing system contributed to improved timber surface quality. The frame controls the chain to consistently saw timber along a straight line, thus contributing to timber size uniformity, while modified angles and depth gauge clearance effectively optimize the sawing speed, reducing erratic behaviour of the saw and producing sawn timber with smooth surface and uniform dimensions.

Due to the optimized parameters, the chainsaw system recovered more timber while proving to be more economical and reducing wood wastes released to the environment. Its ergonomic characteristics were more operator responsive.

3. The optimized design parameters make framed chainsaw an eco-efficient small-scale timber sawing system which is reliable in adding value to tree resources while contributing to environmental conservation through increased timber recovery and quality. The system is recommended for timber sawyers operating on the farms, where trees are few, scattered and small in diameter.

5.2 Recommendations

This study generated several recommendations that were based on the numerous limitations that were identified. These include;

1. The sawing systems (i.e., bench, chain and pit saws) used on farms should be discouraged due to their poor performance. Their continued use jeopardize the gains made by farmers and other stake holders in planting trees in an effort to attain higher forest cover while improving livelihoods through getting financial gains from trees on farms.
2. Framed chain sawing system, with the optimized chains should be adopted for sawing timber on farms to improve on recovery and characteristics of the resultant sawn timber which are currently highly compromised. This is because they support the efforts in conservation of trees on farms, reduce environmental pollution while improving ergonomic characteristics.
3. Chainsaw operators should encouraged to use the framed chainsaw with optimized chain as a way of minimizing injuries and other occupational risks including excessive exposure to vibrations and noise. The frames need to be introduced to local fabricators to make them available and affordable to users.
4. The findings from this study can be used to form a basis for formulation of regulations to help improve efficiency in timber sawing on farms. Such regulations would help in enhancing its adoption in the on-farm timber sawing sub-sector. This would lead to improved timber recovery and higher financial

gains for the tree farmers as well as the timber sawyers, leading to improved livelihoods.

5.3 Areas for Further Research

1. The possibilities of environmental pollution by the on-farm sawing systems including the framed chainsaw systemthrough exhaust gases need to be investigated when the relevant test apparatus become available, to pave way for the development of mitigation measures.
2. There is need for more work to enable further analysis of the effect of the modification of the design parameters on fuel consumption and timber characteristics. This will build on the available data to enhance determination of the optimal parameters for fuel efficiency and timber surface quality.

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APPENDICES

Appendix 1: Statistical-Economic Model for Evaluating Sawing Systems.

Tree characteristics

Species	Tree size	Diameter at breast height av. (cm)	Millable stem length (m)	Likely conversion to defect free timber	Possible sawn timber vol/tree (m^3)	Potential m^3 of log milled per hour
Prosopis	Shrub	20	1.8	25%	0.014	0.15
Grevillea	Small	18	6	45%	0.069	0.3
Grevillea	Medium	32	8	50%	0.322	0.4
Eucalyptus	Large	50	10	55%	1.080	0.5

Type	Tree size	Tree cost (Ksh)	Tree Value (Ksh/m^3)
Prosopis	Shrub	200	3537
Grevillea	Small	550	3602
Grevillea	Medium	1000	1554
Eucalyptus	Large	2000	1019

Tree type to economically assess

	Size	**Stem Form & quality**
	medium	good

Parameters to Assess

US$ to Ksh	81

Felling	
Sawing set-up	
Slabbing	milling of log Refueling Sharpening

Breaks	coffee lunch tea	
Transport	to site away from site timber by	Truck
Buying trees	Search / finding Negotiating Licences & Permits	
		Per person
Labour rate / hour Ksh		10.00

Fuel mix		petrol
	parts mix	5

Days / year working	150

Variable Costs

Fuels/ oils used		litres/day	cost/litre Ksh		
	Petrol	8.5	95		
	2T	0.9	120		
	chain oil	4.2	130		
	Total				

Operating Time and cost		Hours	Labour costs Ksh		
Hours/day slabbing		4.4	88		
Hours/day felling		1.5	30		
Hours/day resting & travelling		1.9	38		
	Total	7.8	156		

Buying trees hours per Year		Hours	Labour costs Ksh
(one person)		375	3,750
Logs		Logs	Cost Ksh
	Log Each	0.64	1000

m3/day milled	1.8		
no. of trees/day	2.7		
Log Costs / day		2725	
m3/year milled	263		
	m3 transported /trip	cost / trip Ksh	Cost per day Ksh
Transport of timber to local market	2.5	2000	701

Maintenance per year	Ksh
Replacement Chains	3,300
Service	800
Chain Files	600
Spares per year averaged	1,000
Total maintenance cost/ year	5,700
Total maintenance cost/day	38

	Ksh
Total running costs / day	5,111
Total running costs / year	766,627

Financial Investment Costs

	Ksh
Purchase Price saw	52,000
Purchase Price frame	27,750

Loan	Ksh	Interest rate	Down payment	Total loan	Yearly loan cost	Total loan cost
			16.5%	#REF!	#REF!	#REF!

Depreciation (straight line)	years life	Residual value	1st year	4th year	5th year	6th year

Chainsaw	Ksh	6	10,000	12,480	5,478	4,164	3,164	1
Frame	Ksh	12	5,000	3,691	2,405	2,085	1,808	1

		1st year	4th year	5th year	6th year
Total financial costs	Ksh	#REF!	7,884	#REF!	#REF!

Other costs

	Ksh
Annual Council Licence	6,000

Processing slabs to finished timber by yard sales person		Hourly rate	Hours worked	Days worked / yr
	Ksh	10	7	230
	US$	$ 0.13		

		Monthly	Yearly
Yard rental	Ksh	5,000	60,000

Revenue

	Sawn timber m^3	% recovery from log
m^3/day sawn	0.88	50%
Linear feet/ day sawn	575	
m^3/year milled	132	

		Ksh
Timber price	/m3	8,858
	/ ft	13.50

Total revenue / day	7,766

Results

Total annual costs	Ksh	1st year	2nd year	3rd year	4th year	5th year
		#REF!	#REF!	#REF!	#REF!	#REF!
Gross income per year	Ksh	1,164,862	1,164,862	1,164,862	1,164,862	1,164,862
Gross margin per year	Ksh	#REF!	#REF!	#REF!	#REF!	#REF!

Performance Evaluation

Chainsaw frame sawing On first year results		Results	per hour of labour	per unit of currency invested in capital	per m^3 of log milled
Total first year costs	Ksh	#REF!	#REF!	#REF!	#REF!
Gross income first year	Ksh	1,164,862	269	15	4,429
Gross margin first year	Ksh	#REF!	#REF!	#REF!	#REF!

Chainsaw frame sawing

		per m^3	per linear foot		
Breakeven timber price	Ksh	#REF!	#REF!	13.5	#REF!

		per litre of fuel used	per linear foot
Breakeven hire out rates	Ksh	#REF!	#REF!

Breakeven milling & selling timber (days)	#REF!
Payback period on saw and frame milling & selling timber (days)	#REF!

Chainsaw frame sawing

Internal Rate of Return (IRR)							
1st year	2nd	3rd year	4th year	5th year	6th year	7th year	8t
Not computable	Not computable	Not computable	Not computable	Not computable	Not computable	Not computable	co

Net Present Value (NPV)		Discount rate 12%	16%	**20%**	24%	28%
Gross margin	Ksh	#REF!	#REF!	**#REF!**	#REF!	#REF!
Costs	Ksh	#REF!	#REF!	**#REF!**	#REF!	#REF!
Revenue	Ksh	5,786,616	5,059,685	**4,469,762**	3,985,252	3,582,875

Sensitivity analysis
% change in 1st year Gross margin

		Factors					
% Change in Factor or % conversion rate or % interest rate (change +ve or -ve sign in factors for -ve % change)		Change in tree costs	Change in fuel costs	Change in labour costs	Change in timber price	% Conversion rate log to sawn timber	% interest rates
-50%		#REF!	#REF!	#REF!	#REF!		
-40%		#REF!	#REF!	#REF!	#REF!		
-30%		#REF!	#REF!	#REF!	#REF!		
-20%		#REF!	#REF!	#REF!	#REF!		
-10%		#REF!	#REF!	#REF!	#REF!		
0%		#REF!	#REF!	#REF!	#REF!		#REF!
10%		#REF!	#REF!	#REF!	#REF!	#REF!	#REF!
20%		#REF!	#REF!	#REF!	#REF!	#REF!	#REF!
30%		#REF!	#REF!	#REF!	#REF!	#REF!	#REF!
40%		#REF!	#REF!	#REF!	#REF!	#REF!	#REF!
50%		#REF!	#REF!	#REF!	#REF!	#REF!	#REF!
60%		#REF!	#REF!	#REF!	#REF!	#REF!	#REF!
70%		#REF!	#REF!	#REF!	#REF!	#REF!	#REF!
80%		#REF!	#REF!	#REF!	#REF!	#REF!	#REF!
90%		#REF!	#REF!	#REF!	#REF!		#REF!
100%		#REF!	#REF!	#REF!	#REF!		#REF!

Appendix 2: Pictorial Presentations.

(a) Wood lots (b) Intercropping (c) Boundary planting

Plate A1: Some of the on-farm tree planting patterns in Kenya

(a) Freehand chainsawing (b) Bench sawing (c) Pit sawing

Plate A2: Sawing systems used for on-farm timber sawing in Kenya

Plate A3: Data capturing in; log measurements (left), ergonomics (vibration and noise level)(centre and right) at the KEFRI timber processing centre

Plate A4: Timber size measurements and surface for timber sawn using freehand chainsaw (centre) and framed chainsaw (right)

Plate A5: Introduction of the framed chainsaw system to users and trials of different operation postures

Plate A6: County Officials take a tour during an On-farm timber sawing field day in Kirinyaga County (Left) and The Kirinyaga County Minister for Environment receives a chainsaw frame on behalf of Kagio chainsaw operators welfare group from a KEFRI/JKUAT Researcher.