DESIGN OF A BRUSH CUTTER BLADE AND ITS INTEGRATION INTO A SEMI MECHANIZED SUGARCANE HARVESTING SYSTEM.

Matthew Innes Langton

Submitted in partial fulfilment of the requirements
for the degree of MSc Engineering

School of Bioresources Engineering and Environmental Hydrology
University of KwaZulu-Natal
Pietermaritzburg
South Africa
2007

DISCLAIMER

I wish to certify that the work reported in this dissertation is my own original and unaided work except where specific acknowledgement is made.

Signed: .... Date: 12/05/2007

M. I. Langton

As the candidates supervisor I have approved this dissertation for submission.

Signed: .... Date: 12/5/07

P.W.L. Lyne

As the candidates supervisor I have approved this dissertation for submission.

Signed: .... Date: ....

C.N. Bezuidenhout

ACKNOWLEGEMENTS

The author wishes to express his sincere appreciation for the assistance given by the following, without whom this research would not have been possible:

- Prof. P.W.L. Lyne, South African Sugarcane Research Institute (SASRI), for supervising this project and providing advice, encouragement and endless assistance throughout the project.
- Dr. C.N. Bezuidenhout, School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, for supervision and endless assistance and encouragement throughout the project.
- Prof. J.C. Smithers, School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu–Natal, for providing support.
- Mr. E. Meyer, South African Sugarcane Research Institute (SASRI), for providing advice, encouragement and endless assistance throughout the project.
- Mr. C. Pfotenhauer, Mr. K. Domleo, Mr. B. Thompson, Mr. J. Bowley and Mr. D. Rein, Illovo Sugar, Sezela, for overseeing, managing the project on the ground, facilitating finance of the project along with supplying important input from the industry's point of view.
- The farm laborers who harvested and assisted in the data capturing.
- Mr. J. Faul and Mr. J. Lyle, Okapi Knives, Mandeni, for supplying the project with readily available blades and having endless ideas and innovations.
- Mr. D. van der Merwe, Andreas Stihl (Pty) Ltd, Pietermaritzburg, for help with a number of aspects of the project. These included technical information on various issues surrounding the brushcutter as well as facilitating the purchase of a brushcutter for the project. He also supplied back-up and assistance in maintaining and repairing damaged machines. As well as supplying numerous innovative ideas.
- Dr. C. Christie, Mr. A. Todd, Mr. A. Cripwell, Mr. A. Elliot, Miss S. Furney and Miss J. Hutchins, Ergonomics Unit, Rhodes University, Grahamstown who performed the ergonomics study and gave valuable information, taught and carried out the data capturing.

- Mr. A. Hill, School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal who manufactured a few critical components for the brushcutter and thus saved the project money and time.
- To my family, especially my Dad and Mom for supporting and financing me.
- To my friends, especially 18 Shores Rd and 77 Hosking Rd for their encouragement and support.
- Finally, to my Lord and Savior, Jesus Christ. To God be the glory, though Him, all things are possible.

ABSTRACT

Sugarcane is an important crop for South Africa. It provides employment and valuable foreign currency that stabilises the country's economy. In South Africa there are three sugarcane harvesting methods available, namely, manual, chopper and whole stalk harvesting of which manual harvesting is currently the dominant harvesting method. However, it is labour intensive and may be sensitive to issues, such as HIV/AIDS and the attractive industrial occupation. The majority of South Africa's sugarcane is planted on steep topographies where mechanical harvesters are unable to operate. It has, therefore, become important to re-evaluate sugarcane cutting systems in an attempt to make sugarcane cutting easier, cheaper and more efficient. The aims for the project were, first, to design a blade that can be attached to a brushcutter to cut sugarcane effectively and efficiently and, second, to integrate the brushcutter into an economically and ergonomically sound sugarcane harvesting system. A harvester was developed called the Illovo Sugarcane Harvester and trials were conducted on the Lower South Coast to assess performance, efficiency, economics and blade durability. A major constraint with the design was the durability of the blade and this limitation contributes significantly to the cost of the system. Using the system it was found to harvest sugarcane effectively and economically but further aspects are outlined for further research. An ergonomic study was performed and results suggest that significantly less energy is required to harvest sugarcane per ton compared to manual harvesting. More energy is, however, required in a work shift and might be detrimental to the labourer. An additional study was performed on the lower back, which is often the leading cause of musculoskeletal disorder experienced in the workplace. Results were favourable and clearly showed that there is less stress and strain on the back when using this system compared to manual harvesting. The system was implemented in a commercial environment and several recommendations were determined.

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1. INTRODUCTION

1.1 Background and Rationale

Sugarcane is a major economic crop in many developing countries, including South Africa, where ample labour for manual harvesting has been available (Meyer, 1997b and Meyer and Fenwick, 2003). However, with rising aspirations and the manufacturing sector providing higher paid jobs with more comfortable working conditions, labour may become scarce in the foreseeable future (de Beer, 1974, Hudson *et al.*, 1976 and Royce, 1996). Currently, approximately 90 % of sugarcane in the world is harvested by hand (Meyer, 1997a). This is a physically strenuous job and causes large stresses and fatigue to the body (Smit *et al.*, 2001, Lambert *et al.*, 2002 and Meyer and Fenwick, 2003). Sugarcane cutters in South Africa are expected to cut and then stack 4 tons of cane per day (Brookes, 1983). If grab loaders are used, sugarcane cutters are expected to cut between 7 and 9 tons per day (Meyer, 1997a). With declining profit margins, farmers in South Africa are unable to pay satisfactory wages and hence, the job has lost its appeal to unskilled labourers. In South Africa this trend grew to the extent that significant tonnages of the crop could not be harvested in 2004. The industry realised the severity of the problem and have been looking for solutions (Boast, 1994).

Internationally, the problem has been partially solved by the increased use of mechanised harvesting systems or chopper harvesters (Meyer, 1997a). Locally, the problem was partially solved with the development of numerous sugarcane harvesters. These include: the Sasex cutter (van der Merwe and Pilcher, 1976); the McConnel machine (Hudson *et al.*, 1976); Sasaby sugarcane harvester (Pilcher and Boast, 1980) and the mini-rotor chopper harvester (Pilcher, 1983 and de Beer and Adey, 1985). These involve large and expensive mechanical harvesters and these are appropriate under optimum conditions, however in South Africa large quantities of sugarcane are produced on areas with steep slopes and rough terrain (de Beer and Boevey, 1977). For the industry to continue to operate profitably, it is critical that an alternative system be developed which is suitable for South African conditions. It would also fill the large void between fully mechanised and manual harvesting systems. It should also be an inexpensive and viable solution that will be easily available. A new method of cutting needs to be developed and analysed to improve efficiencies and supply high quality sugarcane that is fresh and has minimal extraneous matter. The shift toward the new system should be gradual to allow for a complete understanding of mechanisation and to meet the local needs without the pressures accompanying drastic but necessary change in the labour force (Freyou, 1999). A thought was to develop a blade suitable for a brushcutter to harvest sugarcane (Langton and Paterson, 2004).

Preliminary results reported by Langton and Paterson (2004) showed that an adapted brushcutter with a specially designed blade could significantly increase the cutting rate compared to a manual system. This would decrease the pressure on the available cutting force. This system was able to operate on steep slopes and under a variety of conditions. However, more work was required to test new blades and implement the brushcutter into an effective working system.

1.2 Aims and Objectives

The aim was to further develop, refine and field evaluate a new harvesting system that used a commercially available modified brushcutter with specifically designed blades called the Illovo Sugarcane Harvester (ISH).

Specific objectives were set for the project, these were to:

1. Develop a sugar harvesting system that could operate on steep slopes and in a variety of conditions,
2. develop and test blades that cut cane efficiently, were durable and economically viable that were allowed to evolve with experience,
3. determine the most effective, efficient and safest system to harvest sugarcane when using the ISH in parallel to the blade development,
4. evaluate and compare the ergonomics of both the use of the ISH and the current manual system, and
5. evaluate the economics and efficiency of the ISH system.

The research has been spilt into two parts called Part A (Design of the blade and adapting the brushcutter, Chapter 3-4) and Part B (Evaluation of the whole system including the ergonomics, Chapter 5-7). Both Parts A and Parts B worked in parallel so as to complete the project within the specified time schedule and during the sugarcane harvest season (April – December). An overview of the available sugarcane harvesting systems is presented in Chapter 2. The design and development of the ISH, with the emphasis on the development and testing of the blades, is reported in Chapters 3 and 4. Part B looks at the broader picture and how the system fits together. This includes an analysis of the system (productivity, efficiency, safety, and economics) in Chapter 5 and an ergonomic analysis (comparison of the cardiac circulatory system, metabolic system and strains to the skeletal and muscular system) between the ISH and manual harvesting in Chapters 6 and 7. The structure of the document can be clearly seen in the road map, Figure 1.1.

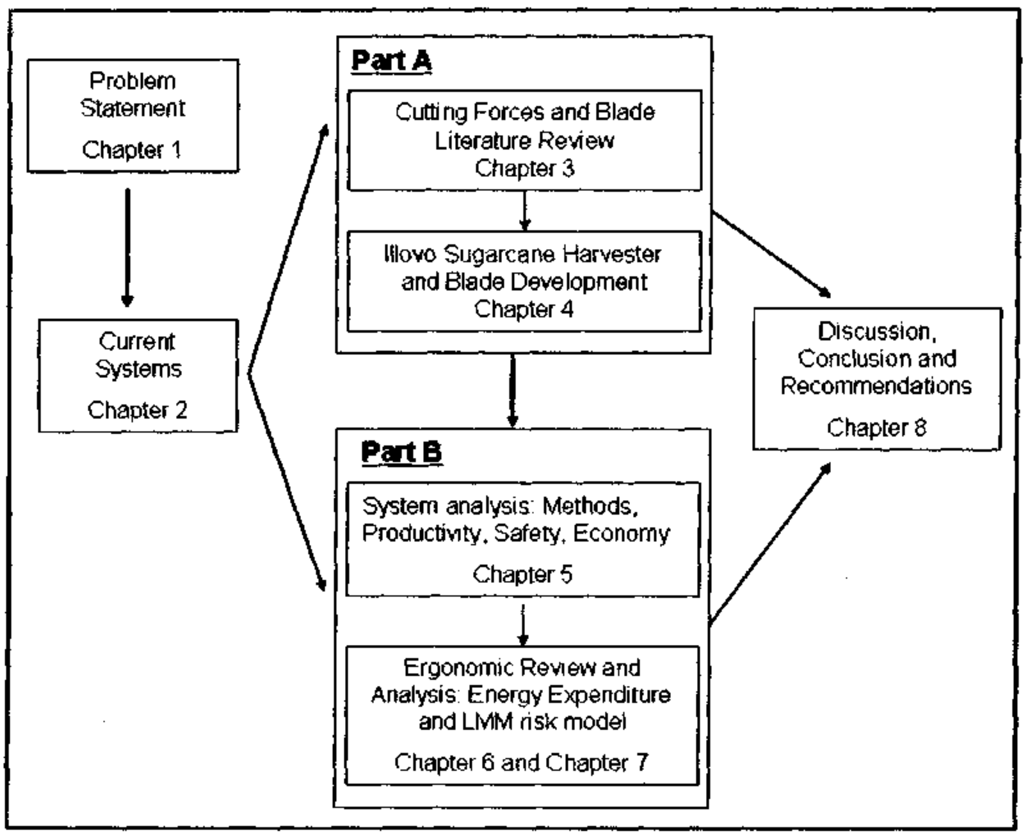

Figure 1.1 Roadmap of the research with Part A dealing with the design and development of the new sugarcane harvesting system and blade and Part B containing the results of the system analyses

2. AN OVERVIEW OF HARVESTING SUGARCANE

Methods of harvesting sugarcane have been in place since the first commercial planting (Blackburn, 1984). New and improved methods are being developed each year to improve efficiencies, to cut down on the delay of delivery to the mill and to operate under a wide range of conditions (Pilcher and van der Merwe, 1976). In South Africa, however, most of the sugarcane is cut by hand due to a high availability of labour and steep topography (Bartlett, 1974). With increasing shortages of labour it is expected that the production of sugarcane in South Africa is going to become more mechanised, similar to the Louisiana sugar industry in the U.S.A., which became fully mechanised in 1950 (Richard *et al.*, 2001).

2.1 Sugarcane Harvesting Systems

An understanding is required of the various systems and the limitations of sugarcane harvesting systems before a decision can be made on which system to implement. The main systems of sugarcane harvesting in South Africa are manual cutting and mechanical harvesting systems, which includes the whole stalk or chopper combine harvesters (Meyer, 1997a).

Over the past 10 years there has been a small but significant increase in mechanised sugarcane harvesting in South Africa (Meyer, 1997a), but the use of mechanisation is accompanied with losses. These losses consist of a number of different factors, including soil compaction and stool damage. Dirt and extraneous matter are also picked up in the field which decreases the harvesting rate, the factory crushing rates, the amount of sugar recovered, and increases transport costs and mill maintenance (Richard *et al.*, 2001). All these factors need to be considered and addressed to achieve higher efficiencies and hence more profit.

2.2 Manual Cutting

The harvesting season in South Africa normally runs from April to December during which a sugarcane cutter will be tasked with a set daily amount to be cut. To avoid the heat of the day, the sugarcane cutter traditionally starts work early in the morning (05h00) and finishes by early afternoon (14h00) (Meyer and Fenwick, 2003).

It is estimated that more than 80% of sugarcane in South Africa is burnt prior to harvesting (Smit *et al.*, 2001). This, however, might change due to pressure from the world market stipulating that farmers must follow burn-free environment friendly practices, also known as green cane harvesting. There are other advantages of green sugarcane harvesting which include having the benefits of a mulch layer and harvesting fresher sugarcane (Whiteing *et al.,* 2001). It is more difficult to harvest green cane due to the cutter having to de-trash the sticks compared to burnt cane as seen in Figure 2.1.

Figure 2.1 Different manual harvesting in green cane on the left and the more preferred and easier method of cutting burnt cane on the right

Two systems of manual cutting are used in South Africa, both predominantly done on burnt sugarcane. These are to cut and bundle (Figure 2.2) and the newer preferred method of cutting lengths or windrows (Figure 2.3). In the cutting lengths system, the cutters are tasked to cut a pre-determined length of row per day. The sugarcane is then laid in windrows where a grab loader transfers the windrow into a vehicle, which transports the cane out the field and to a loading zone. The average performance for some areas is 11.5 tons cut per man-day using the cutting length system (Pocock *et al.*, 1986). This is much higher than the average performance of 4 tons per man-day in the cut and bundle system (Brookes, 1983). In the cutting lengths system there is more compaction and stool damage compared to the bundle system due to the Bell loader making multiple passes during loading. The system also does not operate well in wet and muddy conditions and does not perform well on inclines greater then 44%. The grab loader however, is a very reliable machine and minimal maintenance is required (Pocock *et al.*, 1986). In the bundle system, the bundles are loaded onto self loading trailers and taken to a loading zone where they are off-loaded using a crane (Bartlett, 1974).

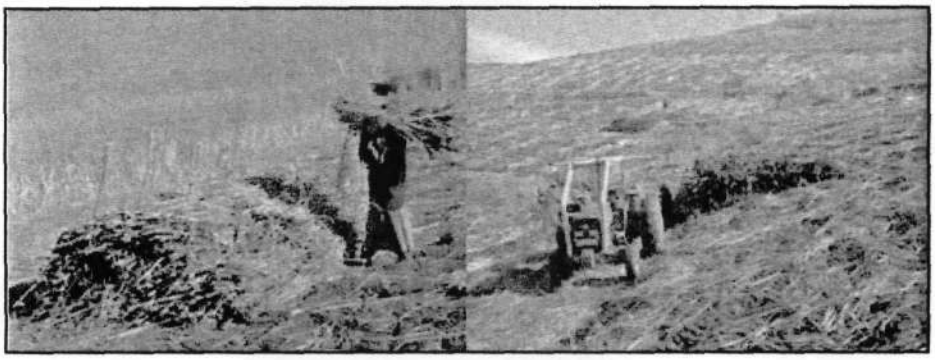

Figure 2.2 Manual cutting and stacking into a bundle which is loaded using a self loading trailer

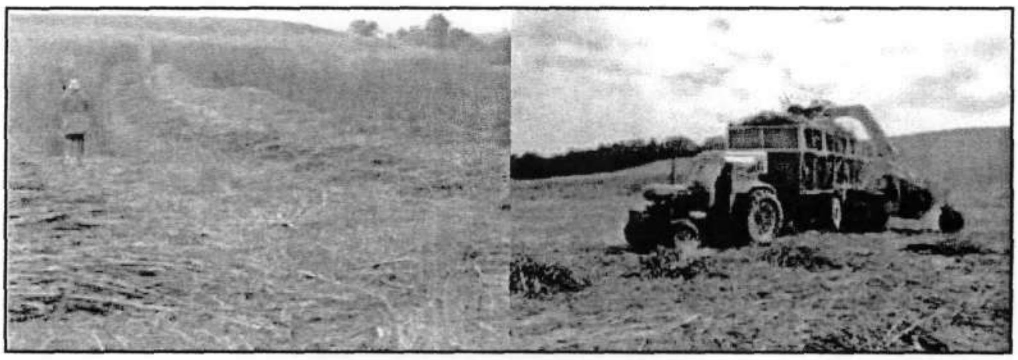

Figure 2.3 Manual cutting into windrows that are picked up by a grab loader and loaded into a vehicle

A new harvesting system was implemented where a split cut and stack system was implemented. Spalding (1992) analysed this system and showed that there was a 54% increase in labour productivity, a 62% improvement in haulage productivity and a decrease in the frequency of disabling injuries compared to the industry standard. However, because this complicates the payment of the labourers, this system is not readily accepted by farm labourers.

Regardless of the system used, it is still essential to maintain a happy and contented harvesting team. The two ways to maintain this are (i) to supply the sugarcane cutter with the best possible tools to do the job and (ii) to maintain an incentive system by paying bonuses on extra sugarcane cut (Bartlett, 1974).

2.2.1 Time study for the cut and bundle system

It is necessary to know where the time is spent in harvesting sugarcane so that changes can be implemented to increase productivity. Meyer and Fenwick (2003) surveyed 58 company estates and conducted motion studies on 12 sugarcane cutters to determine where the time was spent when harvesting sugarcane. An example of how the time was spent can be seen in Figure 2.4. It was noted that higher performing sugarcane cutters spend more time cutting and less time stacking. The total time taken for Cutter 1 was 8.37 hours, during which 4.89 tons of trash sugarcane was cut and stacked. Cutter 2 took 8.42 hours to cut and stack 4.04 tons. It is interesting to note that Cutter 1 cuts more sugarcane in less time.

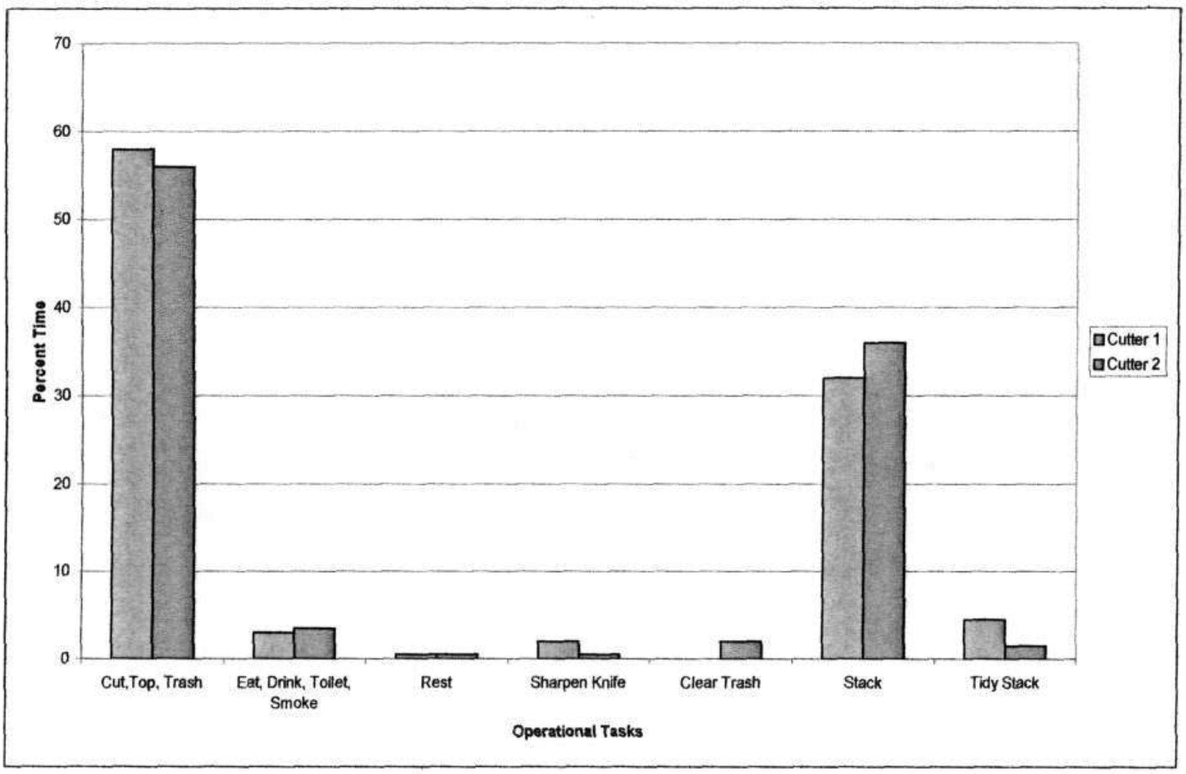

Figure 2.4 Typical percentage time spent by cutters on various activities when cutting and stacking green sugarcane (after Meyer and Fenwick, 2003)

Another factor to consider is the difference in time allocation between different manual harvesting systems. Figure 2.5 shows the various time allocations for stacking burnt or green sugarcane and the cutting and windrowing system. A cutter spent 15% more time cutting green sugarcane compared to burnt sugarcane. In burnt sugarcane, cutters using the cut and windrow system spent 77% of their time cutting compared to 61% in the cut and stacking system. This resulted in 61% more sugarcane being harvested (Meyer and Fenwick, 2003). These results show that if the cutter does not change tasks (from cutting to stacking); then the cutter is able to cut more sugarcane in less time.

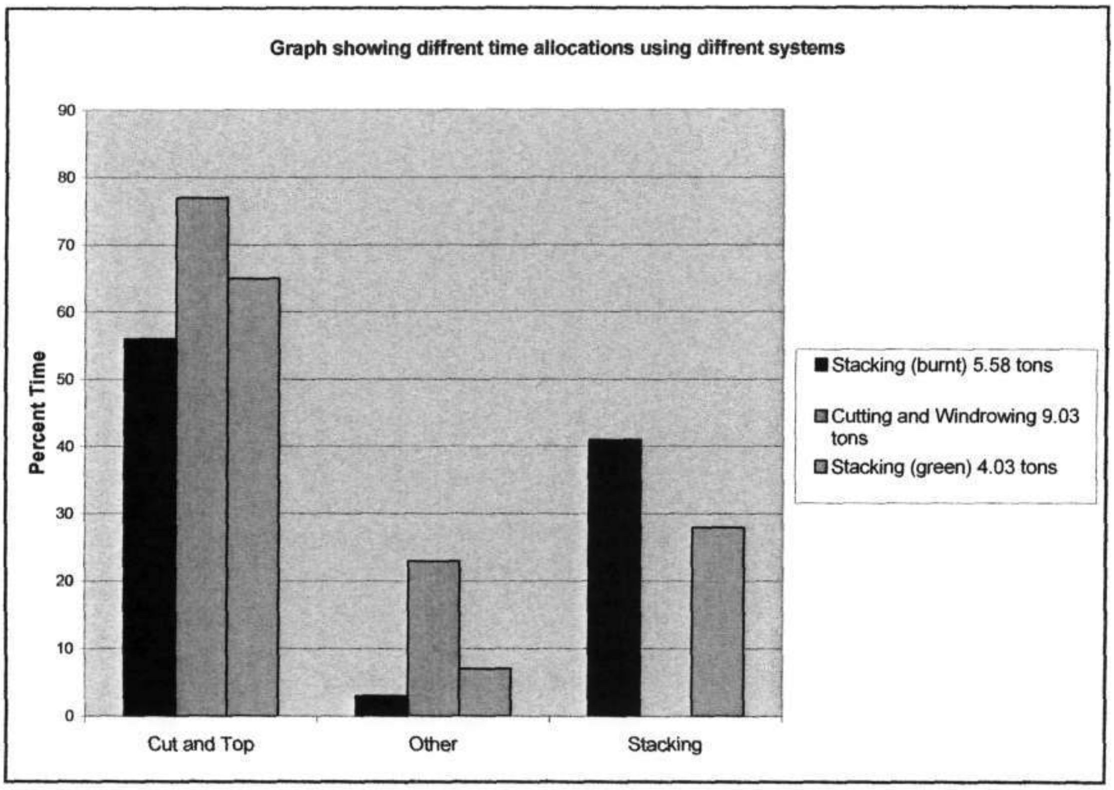

Figure 2.5 Average time (%) spent by cutters on various tasks for three harvesting systems (after Meyer and Fenwick, 2003)

2.2.2 Cutter performance

Brookes (1983) concluded that the following factors contribute to the cutters' performance and productivity:

- Sugarcane characteristics (burnt/trashed, straight/lodged, row spacing, height, yield and quality),
- required standards of cutting accuracy (topping height, base cutting height and trashing),
- methods of working (cutting action, rest pattern and stacking technique),
- knife design and maintenance (e.g. sharpness), and
- quality and quantity of supervision.

As shown in Table 2.1, Meyer and Fenwick (2003) found that there is a larger difference between burnt and green sugarcane then between different systems. However, it is easier to cut more tons per day of sugarcane that has higher yields because the cutter does not have to walk as far.

Table 2.1 Average sugarcane cutter performance for various harvesting systems (after Meyer and Fenwick, 2003)

Harvesting System	Average Yield ($t.ha^{-1}$)	Cutter Output ($t.d^{-1}$)	Cutters per 1000 t
Cut and Stack (green)	72.50	3.45	1.79
Cut and Stack (burnt)	69.60	4.20	1.44
Cut and Bundle (green)	73.94	5.58	1.07
Cut and Bundle (burnt)	69.93	6.56	1.08
Cut and Windrow (burnt)	92.87	8.01	0.99

2.3 Whole Stalk Harvesters

A whole stalk harvester, or soldier harvester as it is commonly referred to, is a system that is not as widely used as the chopper harvesting system. In Louisiana whole stalk harvesters were used exclusively until 1992 after which a transition towards chopper harvesters started (Richard *et al.*, 1996). This was mainly due to the whole stalk harvester being unable to cut lodged sugarcane, which is characteristic of higher yielding varieties (Richard *et al.*, 2001). The whole stalk harvester is still used due to limitations in mill receiving equipment and transport and loading systems (Meyer, 1997a). A whole stalk harvester cuts the sugarcane at the base and removes some of the tops. The sugarcane is then placed into windrows where they are burnt before being loaded into a trailer using a grab loader (Richard *et al.*, 2001).

Blackburn (1984) and Meyer (1997a) outlined some advantages and disadvantages for the whole stalk harvesting system. Advantages include the following:

- Whole stalk harvesters are generally cheaper to purchase than chopper harvesters,
- whole sugarcane sticks deteriorate slower then chopped sugarcane and can be stockpiled,
- whole stalk harvesters are fairly simple machines and are easy to operate, and
- lower losses occur when the field and crop conditions are suitable.

The disadvantages of whole stalk harvesters include the following:

- Lodged sugarcane and sugarcane yielding over $120t.ha^{-1}$ cannot be handled,
- separate infield loading is required,
- the harvester is unstable on slopes greater than 20%, and
- the sugarcane has to be burnt.

2.4 Chopper Harvesters

Chopper harvesters cut burnt or green sugarcane into billets of lengths of approximately 200 mm (Fuelling, 1999). The configuration is similar to the whole stalk harvester and can be seen in Figure 2.6.

As with whole stick harvesters, the stems are gathered and cut at the base, topped and drawn into the machine butt-end first. The sugarcane is then cut into billets either by meshing rollers or by a rotating knife. The sugarcane is then cleaned and the trash is extracted by the primary extractor fan. The billeted sugarcane is conveyed by a secondary extractor into a separate trailer (Bartlett, 1974).

Meyer (1997a) outlined some advantages and disadvantages for this system. The advantages include the following:

- Chopper harvesters are complete combines and do not require additional in-field loading,

- chopper harvesters can handle burnt and trashed sugarcane in a wide range of conditions,
- the delay between harvest and crush is minimal provided that the sugarcane transport is well scheduled and the shorter delay results in a higher sugar extraction,
- spillage of sugarcane is minimised during transport, and
- labour requirements are reduced compared to manual harvesting.

The disadvantages of the chopper harvester include the following:

- Harvesting, transport and milling are all linked and therefore if one component breaks down, the whole operation shuts down,
- mills have to adapt to receiving chopped sugarcane,
- sugarcane losses are higher compared to manual harvesting,
- chopped sugarcane deteriorates faster and should ideally be crushed within 12-14 hours of cutting,
- harvesters cannot operate on uneven fields with slopes greater then 30%,
- a high capital outlay for machinery is necessary,
- high levels of managerial and operator skills and technical support are required, and
- higher infield compaction and stool damage are more likely to occur.

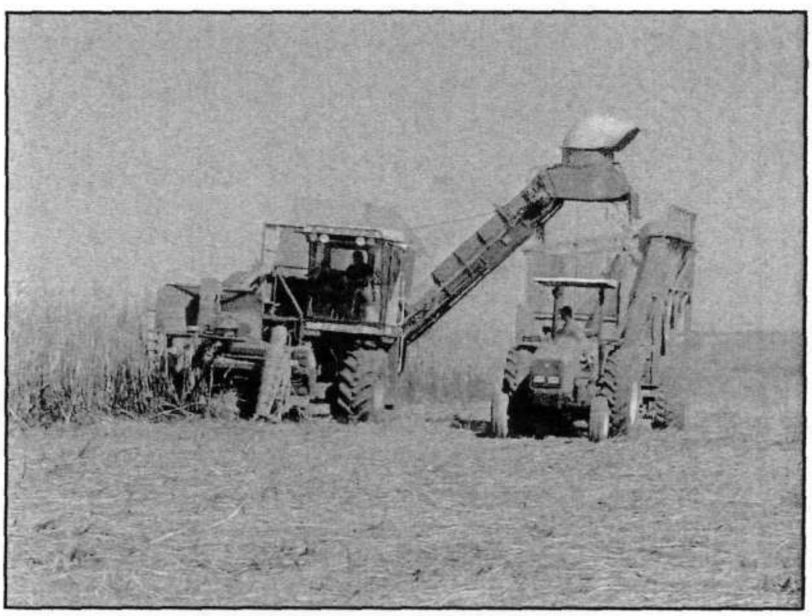

Figure 2.6 A Claas chopper harvester operating in burnt cane and loading directly into a bin trailer

2.5 Comparison of Extraneous Matter and Losses between Systems

Extraneous matter is made up of soil, stools, tops and trash. By minimising these, transport costs and handling are reduced (Richard *et al.*, 2001). Producers are paid for the sugar that can be extracted and inclusion of unnecessary material increases the fibre content which absorbs the extracted juice. Less sugar is thus obtained from the sugarcane and the producer receives less income (Legendre and Richard, 1998). Table 2.2 contains the results from de Beer and Boevey (1977) for extraneous matter and losses found between manual and mechanical harvesting. The mechanical harvesting is comprised of two chopper harvesters, named A and B. The chopper harvesters were identical, but the difference between Chopper A and Chopper B was that Chopper B had not been serviced and was poorly maintained.

Table 2.2 Summary of field losses (after de Beer and Boevey, 1977)

	Manual Hand	Chopper A	Chopper B
Gross sugarcane delivered ($t.ha^{-1}$)	120.1	117.9	108.4
Extraneous matter (%)	3.1	6.1	7.0
Net sugarcane delivered ($t.ha^{-1}$)	116.4	110.8	100.7
Left behind in field ($t.ha^{-1}$)	2.4	3.0	6.1
Loss in millable sugarcane (%)	2.1	6.8	15.3
Loss against hand cut (%)	-	4.8	13.5

From Table 2.2 it is evident that the extraneous matter content for mechanical harvesting system is on average; double that of manual harvesting systems and increases substantially if regular maintenance on the machines is not performed. The sugarcane left behind in the field is a result of not cutting the stalk at ground level and billets being left behind. It is thus evident that it is easier to control the height of cutting manually compared to mechanically.

Meyer *et al.* (2002) showed that there is a slight decrease in losses with later model chopper harvesters (Tables 2.3 and 2.4). Mechanical loaders increased the losses, but are still favorable compared to chopper harvesters. It is also noted that losses increase when operating in green sugarcane, but the advantages of green sugarcane harvesting often out-weigh harvesting losses.

The system that had the least losses was the cut and stack method, which is also the oldest method but labour intensive.

Table 2.3 Summary of manual load systems for sugarcane (after Meyer *et al.*, 2002)

Trial No.	Sugarcane Condition	Loader Type	Infield Transport	Harvested Yield ($t.ha^{-1}$)	Total Loss ($t.ha^{-1}$)	Tota Loss (%)
1	Burnt	Tamhe Grab Loader	10 ton bins	106.79	3.39	3.17
		J&L Continuous Loader	10 ton bins	109.87	4.27	3.89
2	Burnt	Cameco SP 2254 Grab Loader	10 ton bins	78.73	2.13	2.71
		Cameco SP 2254 Grab Loader	Landtrain Spiller trailers	82.02	2.72	3.32
3	Burnt	Cameco SP 2254 Grab Loader	10 ton bins	142.97	2.19	1.53

Table 2.4 Summary of chopper harvested sugarcane (after Meyer *et al.*, 2002)

Trial No.	Sugarcane Condition	Chopper Harvester	Infield Transport	Harvested Yield ($t.ha^{-1}$)	Total Loss ($t.ha^{-1}$)	Total Loss (%)
1	Burnt	Case Austoft 7000	10 ton bins	99.2	3.89	3.77
2	Burnt	Case Austoft 7000	6 ton hi-lift Trailers	79.7	4.25	5.06
		Case Austoft 7000	10 ton bins	86.3	5.05	5.53
	Green	Case Austoft 7000	10 ton bins	81.8	4.82	5.56
3	Burnt	Cameco CHW 2500	10 ton bins	141.53	5.43	3.69
	Green	Cameco CHW 2501	10 ton bins	133.73	7.79	5.5

2.6 Sugarcane Deterioration between Whole Stalk and Chopper Harvesters

Sugarcane starts deteriorating as soon as it is cut and even more so if it is burnt (Meyer, 1997a). Wood (1976) conducted a trial to determine the difference in deterioration between chopped sugarcane and whole stalk sugarcane in January 1976, which had a mean temperature of 24°C. A summary of the results are contained in Tables 2.5 and 2.6.

From Tables 2.5 and 2.6 it is clear that there was a mass loss in both systems but chopper harvested sugarcane deteriorates at more than double the rate, which indicates that it is more susceptible to mill break downs and delays compared to whole stick harvesting. Chopper harvesting requires an efficient and well-organised transport system to minimise these losses.

Table 2.5 Summary of sugarcane deterioration of whole stalk harvested sugarcane (after Wood, 1976)

Day	Fibre (%)	Purity (%)	Units recoverable sugar (%)	Weight gain (%)
0	11.5	85.8	100	-
1	11.0	83.5	92	-2
2	11.7	82.3	93	-2.7
3	11.3	85.7	100	-5.8
4	12.4	84.1	102	-3.8
5	11.9	87.9	107	-5.7

Table 2.6 Summary of sugarcane deterioration of chopped/billeted sugarcane (after Wood, 1976)

Day	Fibre (%)	Purity (%)	Units recoverable sugar (%)	Weight gain (%)
0	11.9	88.2	100	-
1	12.1	87.5	96	-3.1
2	12	86.2	93	-6.7
3	11.5	82.7	84	-9.3
4	11.6	77.9	72	-15.6
5	11.3	80.1	77	-14.8

2.7 Summary of Systems

The three systems are manual sugarcane cutting, whole stalk harvesting and chopper harvesting. The whole stalk harvester is not readily available in South Africa and farmers in South Africa mainly choose between manual harvesting and chopper harvesting. Manual sugarcane harvesting has the least losses but it is very labour intensive. Labour, however, is becoming scarce and many areas are not able to implement chopper harvesters due to the steep topography. New methods are thus required to harvest sugarcane efficiently that can also operate on steep slopes.

PART A: DESIGN OF THE ILLOVO SUGARCANE HARVESTER

3. LITERATURE REVIEW OF CUTTING FORCES AND BLADES

From Chapter 2 it is evident that the majority of time when harvesting sugarcane is spent during cutting operations. A small increase in the cutting productivity would hence have the largest effect on the system. In order to investigate methods to increase productivity a review of the cutting forces and design of new tools and implements was carried out.

3.1 Sugarcane Structure

The material required to be cut is sugarcane, which is a tall tropical grass; it forms a single unbranched stalk that reaches an average height of 3-4m. The stem diameter ranges from 2.5 to 5cm. The plant consists of solid material, liquid and air-filled spaces (Blackburn, 1984). The fibre cells that are arranged in bundle spirals, called microfibrils, provide the stalk's strength. The stem is divided into nodal and internodal spaces (Figure 3.1). The internodal space is weaker than the node, but the cutting force required is determined in the internodal space (Blackburn, 1984). This is due to the cut taking place at ground level where it is predominantly at the internodal space.

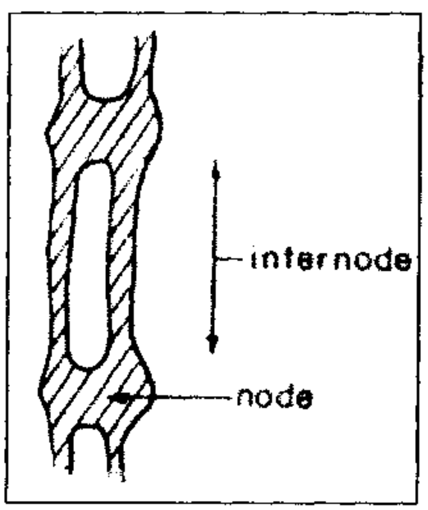

Figure 3.1 Longitudinal section through a stem showing nodes and internodes (Persson, 1987)

3.2 Cutting Forces

The length of cut and shearing resistance of plant material influences the power required to cut. The cutting energy required is difficult to estimate and is dependent on blade sharpness, blade bevel angle, aggregate thickness and blade velocity (Richey, 1958). However, if the knives are correctly bevelled and sharpened, the energy requirements depend mostly on the plant aggregate thickness (Chancellor, 1958). The greater the aggregate thickness, the greater the energy required and the higher the forces required for cutting. It is believed that, with increased thickness, a greater force is required to compress the material to a firmness that will permit cutting and failure (Persson, 1987).

Kroes and Harris (1996) did a comprehensive study on the cutting force (F_c) required. The study used a rotary shaft encoder to measure the speed of the blades and a piezo-electric force transducer to measure the force. A typical cutting force versus time curve can be seen in Figure 3.2 for a pure impact cut. F_c is the force in Newtons with a peak of 430N. The smaller peaks are presumed to be the friction between the fibres and the blade. This was done on a variety of cane called Q124 with an average diameter of 27.8mm.

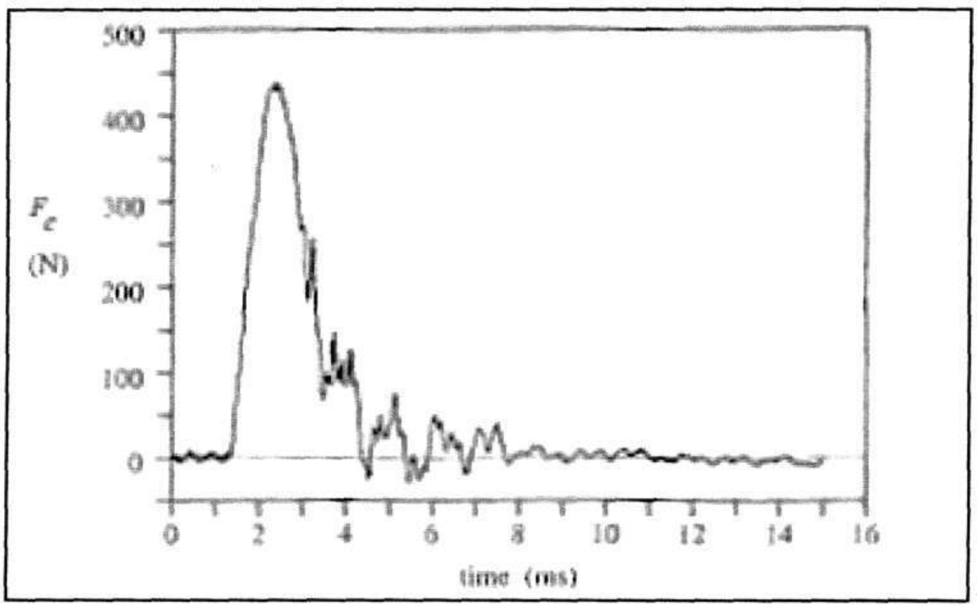

Figure 3.2 Cutting force (F_c) versus time for a sugarcane stalk Q124 with a diameter of 27.8mm, with a maximum force of 430N required to cut sugarcane (Kroes and Harris, 1996)

3.3 Cutting Methods

There are many different types of cutting methods, but for sugarcane the dominant processes are impact and slicing cuts (Persson, 1987). These different cutting methods affect the material differently and can cause losses in the yield. The ability to distinguish between efficient methods and inefficient methods can help a design engineer select the most appropriate cutting device.

Devices that use impact cuts are mowers and manual cane knives which have no countershear to offer support to the cutting process. The necessary reaction forces are provided by the inertia and anchoring of the plant. The impact depends on the plant mass, knife velocity, height of cut above ground, height of plant center of gravity above the ground, stem diameter, bending resistance and cutting force applied (Kroes and Harris, 1997). The controllable variables when cutting sugarcane are the knife velocity, height of cut above the ground and cutting force applied. To minimise cane damage, the blade impact speed must not be reduced below $14 ms^{-1}$ for low fibre cane varieties and $17\ ms^{-1}$ for high fibre cane varieties (Kroes and Harris, 1997).

Chancellor (1958) stated that a slicing cut is when the knife blade friction causes the fibres or parts of fibres to adhere to the knife-edge. As the movement continues, the fibres become separated from the rest of the stem in the region of the knife, but are still attached. As they become further separated the fibers are stressed in pure tension and hence fail. This process takes more energy, but can be achieved using smaller forces since only a few fibers are involved at any one time. Using a serrated edge will have the same effect, but will be more energy efficient.

3.3.1 Cutting using curved and serrated blades

Mello and Harris (1999) conducted a kinematic analysis with a curved edge that was designed with five angles, being 26.7; 22.7; 19.4; 16.7; and 14.5 degrees. These angles relate the angle between the blade edge and the disk tangent, as illustrated in Figure 3.3. This angle is the major parameter between the ratio of a slicing and impact cut. The smaller the angle the greater the slicing action and in contrary, a pure impact cut would have an angle of 90 degrees. The blades at these angles were tested with different serrations as seen in Figure 3.4.

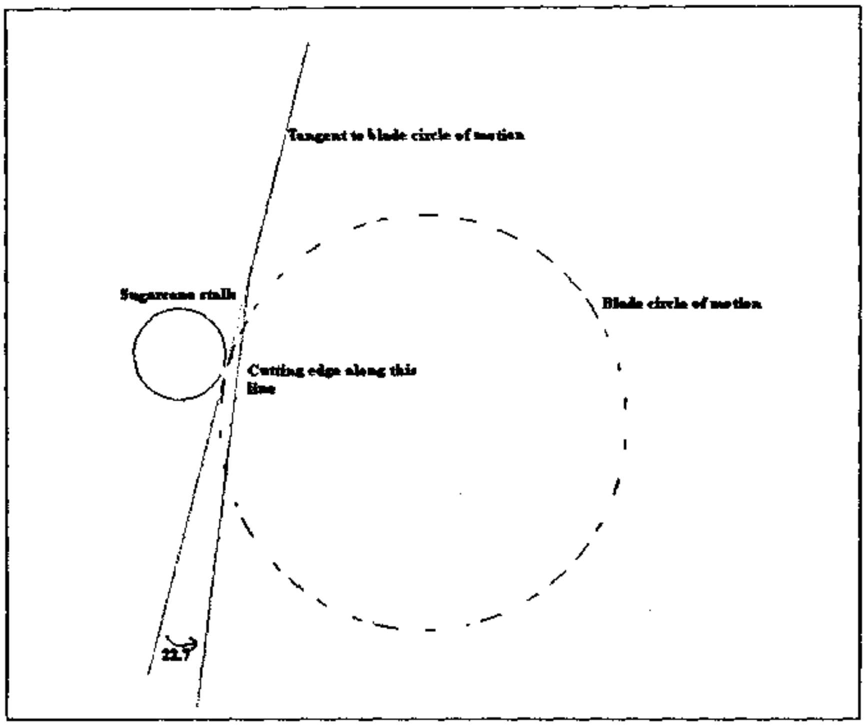

Figure 3.3 Schematic diagram showing the blade angle from above

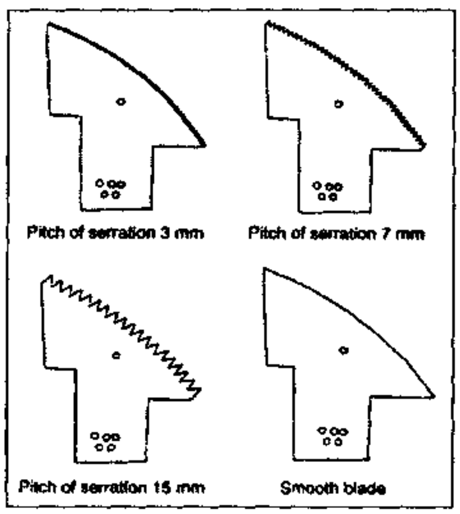

Figure 3.4 Blades with different pitches of serration (Mello and Harris, 2000)

An analysis was done with the losses in the cane during cutting and the damage done to the cane. The different blades were rated according to Kroes (1997) damage rating scale seen in Figure 3.5 at the various angles and different serration pitches.

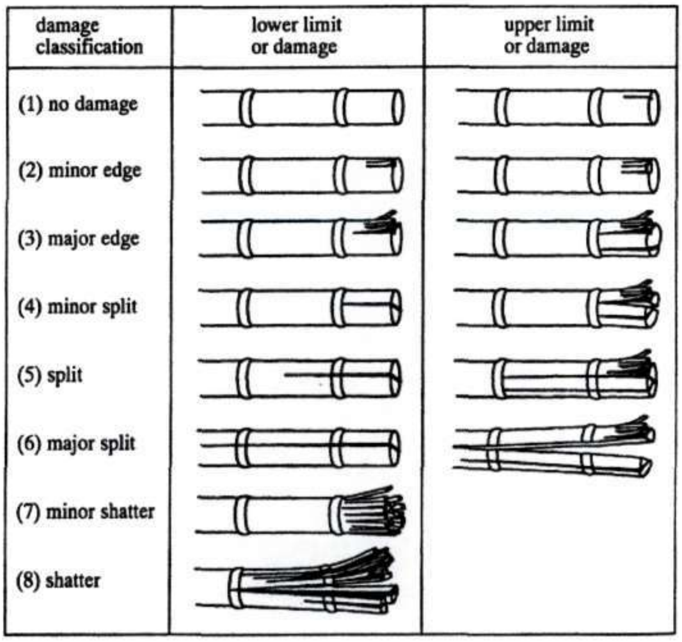

Figure 3.5 Damage classification in cutting processers (Kroes, 1997)

Mello and Harris (2000) results are depicted in Figure 3.6 and Figure 3.7 which shows that the optimal angle to use is 22.7 degrees. Serrations affected losses the most severely at angles of 16.7 and 26.7 degrees. It must be noted that at the optimal angle of 22.7 degrees, the serrations do not have a significant effect on the losses or the damage done.

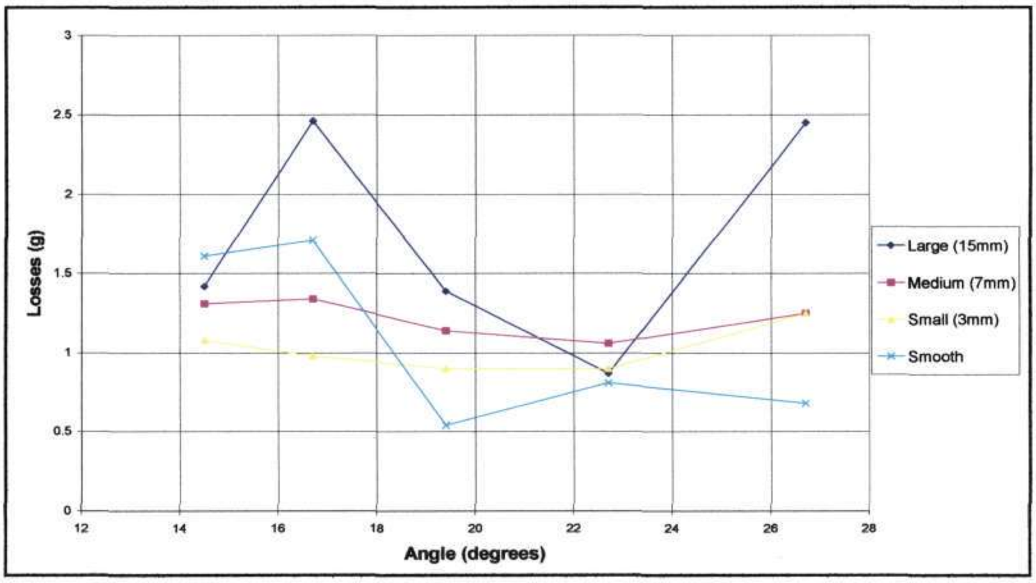

Figure 3.6 Variation of losses for each kind of serration at different angles (after Mello and Harris, 2000)

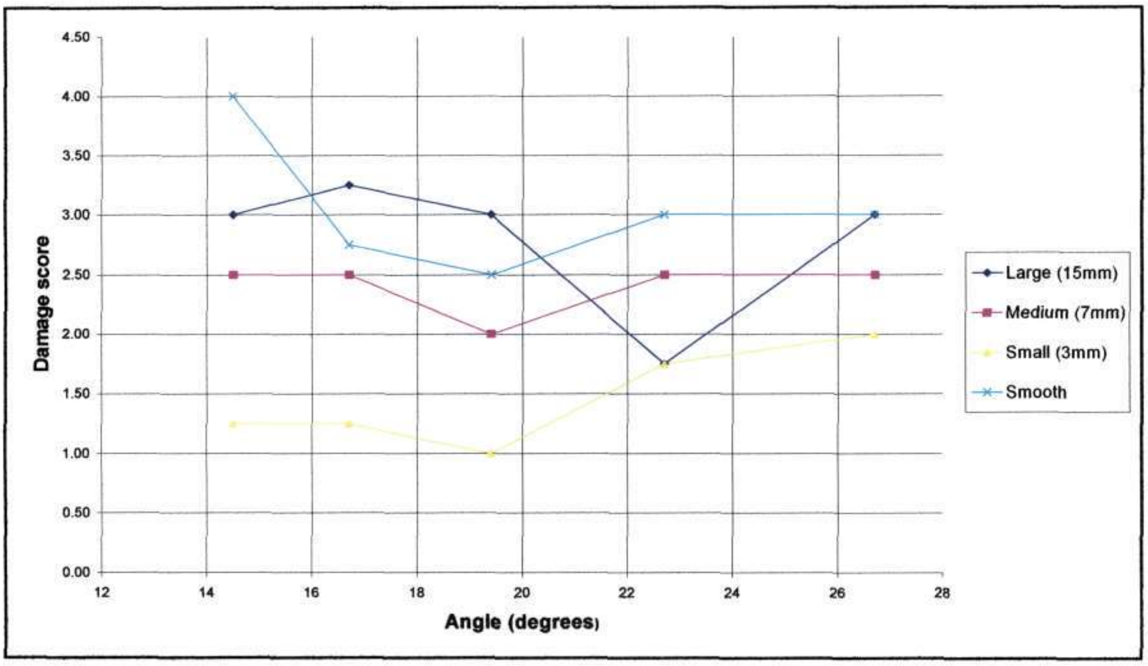

Figure 3.7 Variation of damage rating for each kind of serration (after Mello and Harris, 2000)

3.3.2 Cutting with a countershear

Modern sugarcane harvesters use a double disc basecutter with multiple straight blades. The manual cane knife also uses a straight blade. These blades cut the sugarcane using an impact cut that can cause splitting and potential losses (Kroes, 1997). A pure slicing cut action was suggested to minimise the impact related losses but it was shown that this action did not cut the cane, but rather pushed it to one side (Mello and Harris, 1999). A countershear that prevented the cane being pushed over was thus implemented and tests showed that serrated, curved blades require less energy and the damages incurred during cutting were reduced. A rotating countershear as shown in Figure 3.8 could also be implemented to lower the knife speed so that it was safer to operate (Mello and Harris, 2000). The countershear rotated in the opposite direction of the cutting disk and was positioned above the blade. The collecting edge pulled the plant material in toward the knife where it was cut. The speeds were reduced in the knife since the counter-shear fingers create the necessary reaction forces and were hence, not as dependent on the speed of the blade.

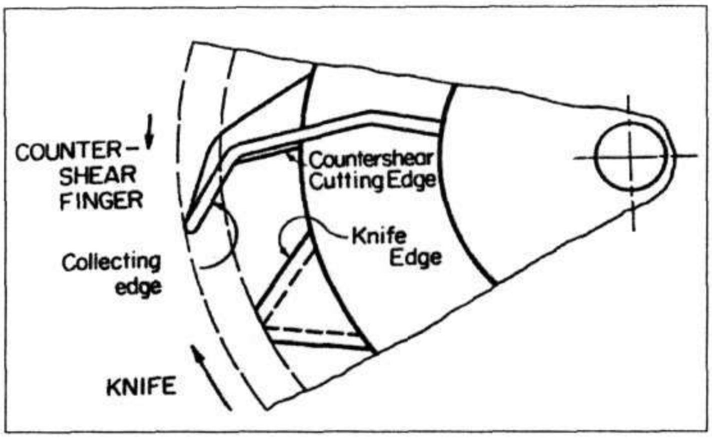

Figure 3.8 Top view of the counter shear finger and knife (Persson, 1993)

3.4 Knife Edges

According to Persson (1987), a knife consists of an edge and the blade where the edge is part of the blade. The edge starts where the blade begins to taper and is seen as the shaded section in Figure 3.9. Three other important features of the knife are also illustrated in Figure 3.9. These are:

1. The edge angle (ANE) that is defined as the angle between the two cutting face's called fineness,
2. edge radius (LRE), which defines the knife sharpness, and
3. edge thickness (LTE) or dullness of the knife.

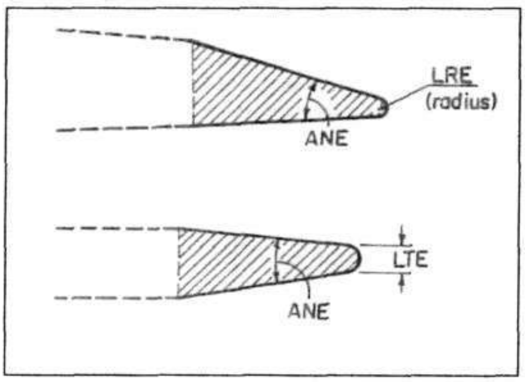

Figure 3.9 Dimensions of a knife to illustrate the edge angle (ANE), edge radius or knife sharpness (LRE) and the edge thickness or dullness (LTE) (Persson, 1987)

The knife should be made from a material that is harder than what is to be cut. A gradual deformation of the blade can be expected due to wear and prolonged use. Steel, or a steel alloy, is favoured because of its hardness and high tensile strength (Neves *et al.*, 2001). Blades commonly used in sugarcane harvesters are made from SAE 5160 spring steel with a 49 HRC hardness (Mello and Harris, 2000).

The sharpness (LRE, Figure 3.9) of a knife is the property that determines the magnitude of the force for initial penetration of the material. The dullness is the opposite of sharpness and is related to LTE (Iga and Finner, 1975). Tests conducted by Chancellor (1958) showed that both the force and energy requirements increase with blade dullness. The force increases until a definite degree of dullness is reached, after which further dullness does not change the force and energy required. Chancellor (1958) also observed a critical value of edge thickness (LTE) that is reached due to wear and depends on the coarseness of the material. Hence, an extremely sharp blade will be rapidly dulled to a given thickness during harvesting (Chancellor, 1958). The force and energy required only increases when the fineness (ANE) exceeds an angle of 30°. Chancellor (1958) determined that the most efficient fineness was at an angle of 24°. Any angles smaller than 24° were subject to rapid wear and dulling.

3.5 Sugarcane Chopper Harvester Base Cutter Blade Wear

Neves *et al.* (2001) compared the current wear of chopper harvester blades to blades fitted on a floating mechanism that prevents the blades cutting the soil. The blades were made from SAE 5160 spring steel, which is a widely used product. The blade was replaced once it reached 95.6% of its original mass since the blades lose their effectiveness if used any further. Mass reductions of 4.4% were found to be reached sooner on the standard chopper harvester (25.1 hours) compared to the floating mechanism (62.7 hours). It can be seen in Figure 3.10 that the amount of wear for the different blades operating for similar times and in similar conditions for the fixed and for the floating base cutter.

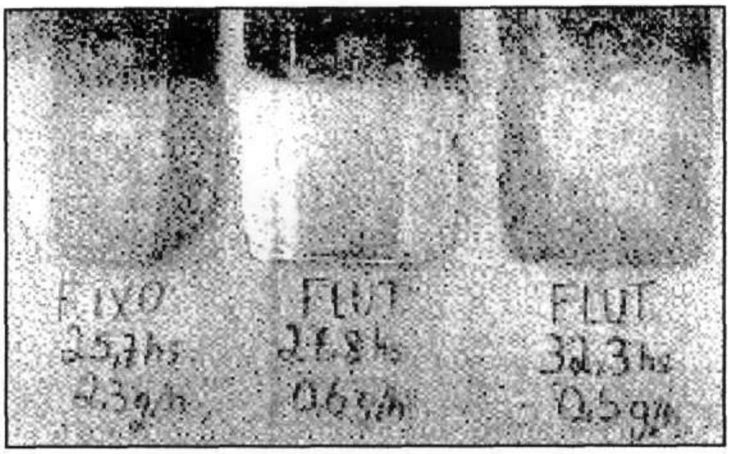

Figure 3.10 Blade wear on the fixed cutter (FIXD) that regularly cuts below the soil surface and for the floating cutter (FLUT) that does not cut below ground level. (Neves *et al,* 2001)

3.6 Summary

Sugarcane is a hard material and requires a maximum cutting force of approximately 430N (Figure 3.2, page 16) for a pure impact cut. By using a slicing blade it is possible to decrease the required force and hence the energy to cut sugarcane. The research shows that the optimal blade for all types of serrations and configurations is a blade with a 22.7 degree cutting angle that combines slicing and impact cutting at a 75% and 25% ratio respectively. A countershear could be implemented to reduce the speed of the blade for safety reasons or if the material to be cut is being pushed to one side but is impractical. The sharpness or fineness of the blade must not be less then 24 degrees or else rapid dulling will be experienced and not greater then 30 degrees or else significantly higher energy is required for penetration. From these findings a blade could be developed and attached to a modified brushcutter specifically made to harvest sugarcane.

4. DEVELOPMENT OF THE ILLOVO SUGARCANE HARVESTER

4.1 Introduction

During the 2004, 2005 and 2006 sugarcane harvesting seasons, work was done to develop a new harvesting method. From the literature review in Chapter 2, it was noted that the largest percentage of time was spent on cutting, therefore a device that increases the cutting speed would result in the most significant saving. After assessing various techniques it was decided to adapt a brushcutter to harvest sugarcane. It was expected that such a machine would be able to harvest under a range of conditions, including steep slopes and areas inaccessible to chopper harvesters. One of the most challenging components was the development of the blade to harvest sugarcane. A requirement was cutting close to the ground to minimise the losses and to cut the cane cleanly so that the cane would ratoon satisfactorily. Figure 4.1 shows a flow chart of the design process for the ISH.

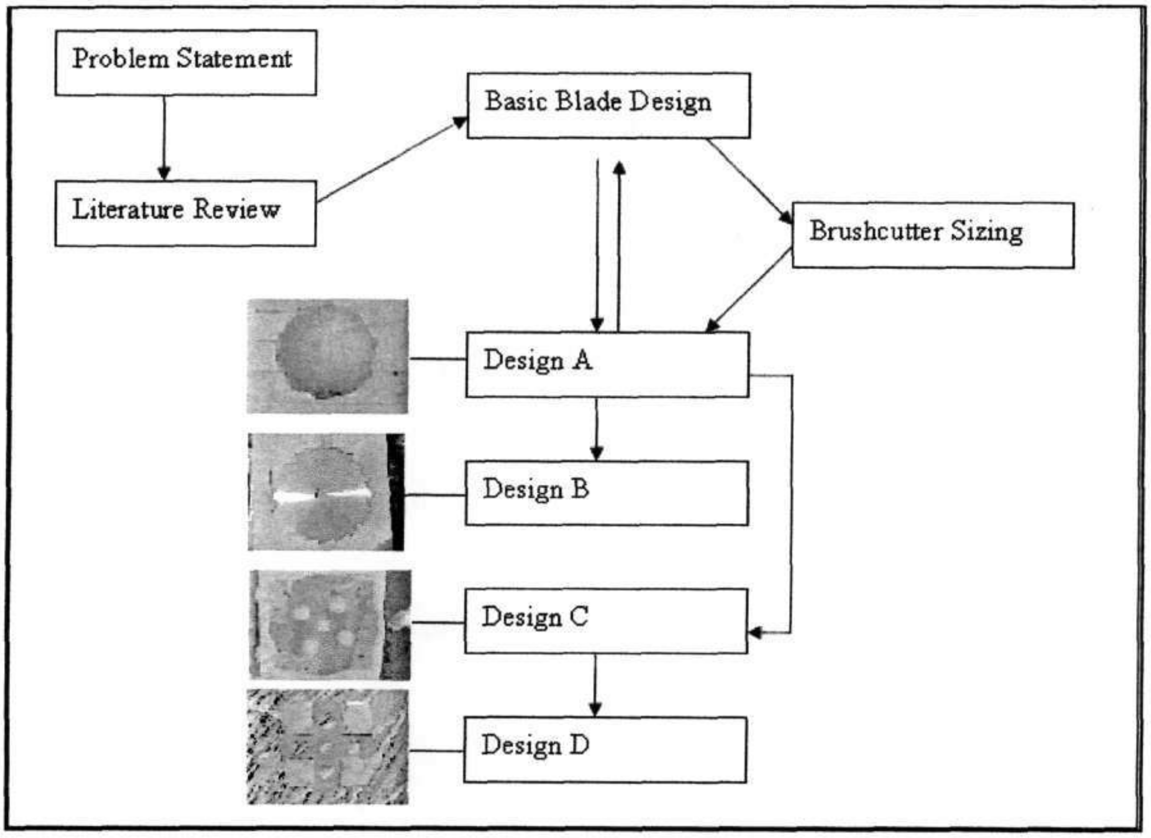

Figure 4.1 Flow chart showing design process of the Illovo Sugarcane Harvester

The blade required a number of design constraints outlined as follows:

1. It required to be attached to a standard commercial brushcutter,
2. the blade had to operate at high speeds (6000 rpm-9000 rpm),
3. the blade mass should not exceed 1.5 kg,
4. it should cut the cane as close to the ground as possible,
5. it should cut the cane cleanly and without damaging the stool,
6. required to be safe to use, and
7. be economically viable.

The above constraints were considered during the design and to make it viable, certain aspects had to be compromised to allow the blade to meet all the above criteria. Once the brushcutter was sized for the basic blade it was not re-sized since it was not practical to continually re-size and purchase new machines. Some blades that were tested and failed, were not put into the design procedure. These will however be mentioned with their limitations where appropriate.

4.2 Basic Blade Design from First Principles

Blades for the system were designed using a combination of results from the literature and outcomes from preceding experiments. Commercially available blades that were tested included multi – toothed (tungsten tipped) and heavier 3–toothed blades. These had been used in private experiments but flaws were found with them (van der Merwe, 2004). The multi–toothed blades cut the sugarcane effectively, but had a short life span with respect to sharpness. The 3–toothed blade performed satisfactorily, but damage occurred in the gearing head of the brush cutter. This was due to a combination of the interval between strikes (higher impact spike loading) on the sugarcane and possibly an underpowered motor. Previous experiments were undertaken using a 1.9 kW brushcutter which was the most powerful at the time.

The literature review indicated that the optimum angle for a slicing cut was a 22.7 degree to the tangent to the circle of motion of the blade (Mello and Harris, 1999). A 10–edged blade was designed using this information and can be seen in Figure 4.2. It used a 75% slicing cut with a 25% impact cut to the sugarcane. More detailed dimensions are available in Appendix A. The thickness of the blade was 4 mm which was the same thickness as the commercial blades used. This dimension however was modified to 2.8 mm and 2.0mm to decrease the weight of the blade.

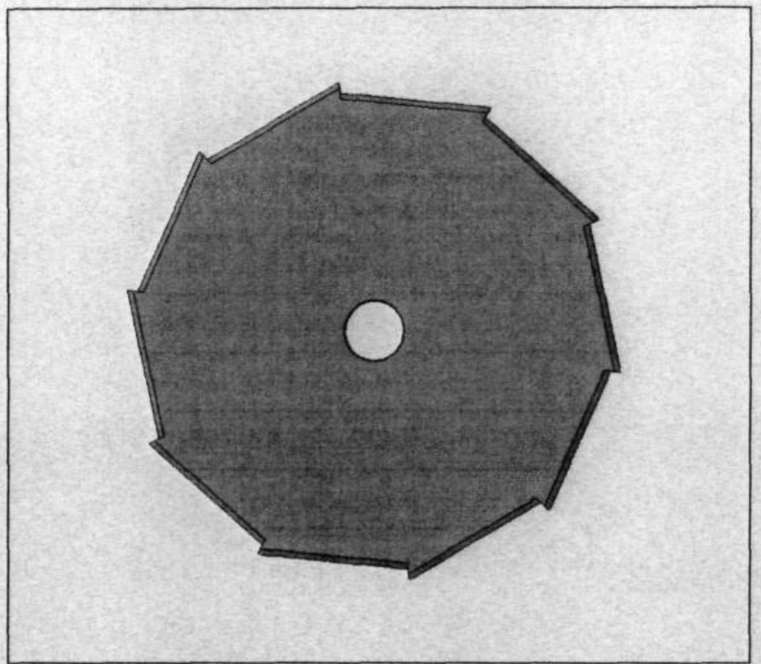

Figure 4.2 Top view of the slicing blade. The blade rotates counter – clockwise

4.3 Brushcutter Adaptation and Sizing

Once the blade was designed it needed to be attached and sized correctly for a conventional brushcutter. Brushcutters are implements that have been in use in South Africa for a number of years. They are readily available and easily serviced. A brushcutter usually consists of a two-stroke petrol motor driving an attachment/blade via a shaft. It is portable, manoeuvrable and harnessed to the operator as seen in Figure 4.3. A high degree of research has gone into the development of commercial brushcutters, e.g. by Andreas Stihl (Pty) Ltd, and the quality of the product is hence assured. Information on the product is readily available for research purposes and mechanical backup and servicing can also be obtained. The brushcutter is in use in a number of industries where cutting is its only function, and it was assumed that only minor modifications would be needed to enable it cut sugarcane. The wide variety of brushcutters available also means that an appropriate motor for the project could easily be specified.

Figure 4.3 Operator with harness and safety equipment

4.3.1 Force and power requirements

An important aspect of the project was determining the force to cut sugarcane and the motor it would require to provide the necessary power. The maximum cutting force determined from Figure 3.2 (pg 16) was approximately 430 N for a pure impact cut. Srivastava *et al.* (1993) stated that a pure slicing cut requires no force to cut. Applying the relevant angles the force required is a quarter for the 10 edged slicing cut i.e. 108 N. For proper cutting of the sugarcane the motor's power must be large enough to supply the necessary cutting force.

Using Equation 4.1 from Srivastava *et al.* (1993), and the relevant required force, the power was obtained for the blade.

$$P_{cut} = \frac{C_F F_{x\max} X_{bu} f_{cut}}{60000} \tag{4.1}$$

Where:

P_{cut} = power for cutting (kW)

F_{xmax} = maximum cutting force (kN)

X_{bu} = depth of material at initial contact with knife (mm)

f_{cut} = cutting frequency (cuts.min^{-1})

C_F = ratio of average to peak cutting force

A C_F value of 0.64 was obtained from a typical force-displacement curve according to Srivastava *et al.* 1993 (Fig 8.15). The force required to cut was 0.108 kN and the X_{bu} value of 25mm was used during testing of the required forces to cut sugarcane (Kroes and Harris, 1996). The f_{cut} was found by multiplying the speed (6000 rpm) by the number of cutting edges per revolution (10) that resulted in a f_{cut} of 60 000 cuts.min^{-1}. This resulted in a P_{cut} of 1.73 kW.

4.3.2 Motor required

The wide variety of motors available allow for a motor well suited to the task of cutting sugarcane to be chosen, as seen in Table 4.1. The choice of motor was also facilitated by reports of previous experiments with brushcutters cutting sugarcane (van der Merwe, 2004). A compromise between power and cost had to be made. A high-powered motor would be very well suited to cutting sugarcane but very expensive whereas a smaller motor would have a reduced life. From the information a STIHL FS 500 was chosen that is rated at 2.4kW. The over specification was due to the FS 500 having more robust components that would be more durable under harsh conditions.

Table 4.1 Specifications of various STIHL brushcutters

Brushcutter Model	Motor Power (kW) n = 1/min	Idle Speed rpm × 1000	Torque on Blade Nm
FS 400	1.9 9000	2.8	14
FS 450	2.1 9000	2.8	14
FS 500	2.4 9500	2.5	14
FS 550	2.8 9500	2.5	14

4.3.3 Machine adaptations

For the machines to be economically viable they were assumed to last for a minimum of one year or one harvesting season (± 9 months). Some adaptations were needed for the brushcutter to be able to sustain harsh conditions and to cut sugarcane effectively.

SPACER

The blade was required to cut as close too ground level as possible since the highest percentage of sugar is located at the bottom of the stalk (De Beer and Boevey, 1977). For the blade to cut low to the ground a spacer was needed. A spacer drops the blade lower on the drive shaft so that no protruding bolt is needed. This allows the blade to cut flush with the ground. Spacers are commercially available and are made from an aluminium alloy seen in Figure 4.4 and more information is available in Appendix A.

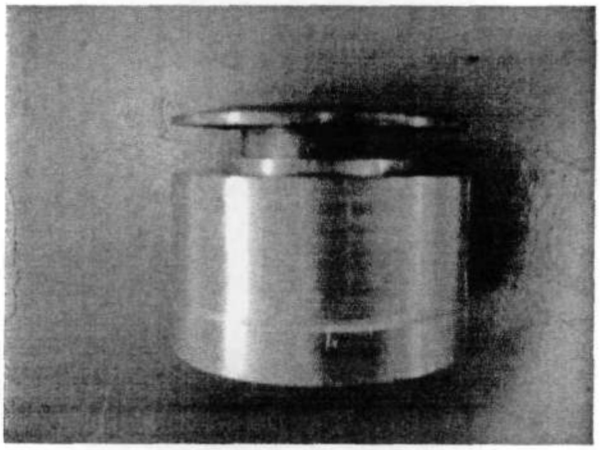

Figure 4.4 Spacer to enable cutters to cut close to the ground

AIR FILTER

The second adaptation was to the air filter. The original filter was a felt filter that needed to be changed on average every 80min. As the filter blocked the motor's rpm dropped causing the engine to labour with the load. A larger more robust filter that is normally used under harsh working conditions in the timber industry was tested and performed better. This filter can be seen in Figure 4.5.

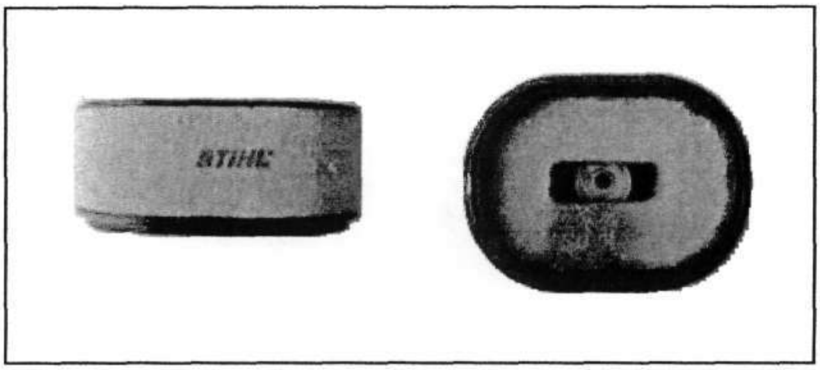

Figure 4.5 Higher capacity robust filter

SELF TAPPING SCREW TO GEAR HEAD

The gear head was originally held on using a clamp screw but this was found to be unsatisfactory. Due to the weight and torque caused by the blade, the gear head came loose several times. To prevent this, a hole was drilled through the gear head and into the shaft (Figure 4.6) and a self tapping screw was then inserted that stopped the gear head from sliding off the shaft.

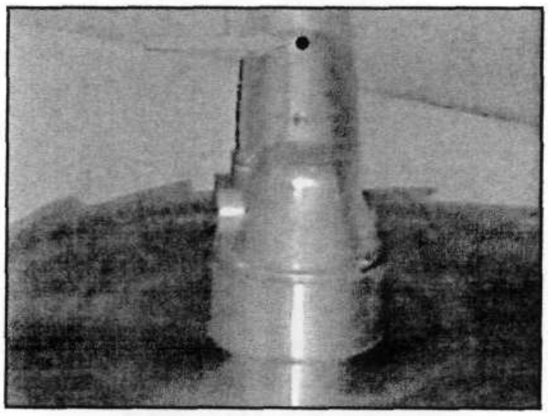

Figure 4.6 Self tapping screw drilled through the gear head to stop it coming off

4.4 Blade Design A

The design process took a stepwise approach. A design was implemented and analysed where after it was possible to determine the problems and hence refine the blade. Each design (Design A to D) will be discussed, results will be reflected and limitations and recommendations will be made.

The first design was the starting point and followed the design outlined in Chapter 4.1. The material used was AISI 1055 (En9, 070M55) with a tensile strength of 850 –1000 MPa and had a minimum yield stress of 570 MPa. This was then hardened to range of Rc between 40 and 55. The harder the Rc value the higher the resistance to wear but the more brittle the metal became. For safety reasons the Rc was increased gradually in testing. The design can be seen in Figure 4.7, the blade rotates in a clockwise direction. Detailed drawings are given in Appendix A.

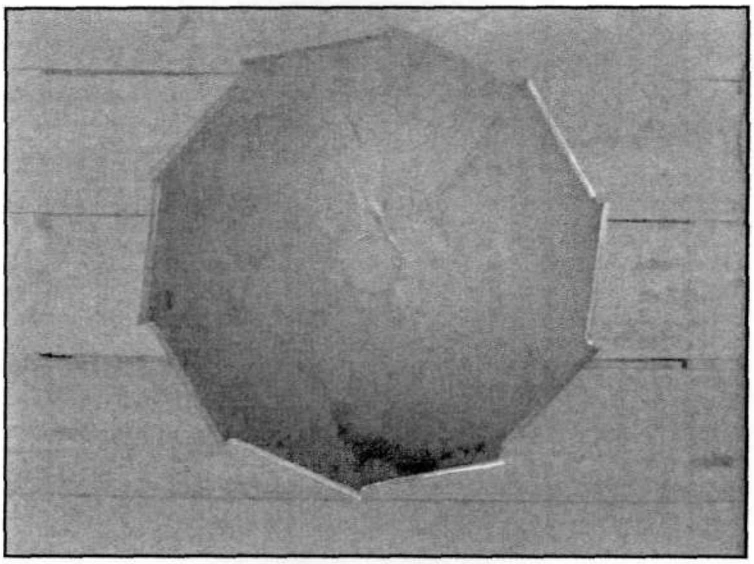

Figure 4.7 Bottom view of Design A with 10 edges that cuts in a clockwise direction

4.4.1 Design A: Results and discussion

The results have been split into three aspects, namely, cut quality, height of cut, blade wear and safety. These were evaluated and recommendations were made.

CUT QUALITY

The cut quality evaluation used was according to the Kroes (1997) damage rating scale (Figure 3.5, pg 19). Design A performed well and had a low damage rating of approximately 1.16. Manual harvesting achieves a damage rating score of between 1 and 2. A clean cut that did not shatter the stools was because of the slicing action of Design A. This supports the theory obtained from Mello and Harris (1999) that a 22.7 degree angle was an effective cutting angle for sugarcane.

HEIGHT OF CUT

An industry standard for sugar cane is that for every foot of stick of cane there is approximately 10 tons per acre in the field. The relationship can be seen in Equation 4.2.

$$1\text{mm of cane} = 0.081 \text{ tons.hectare}^{-1} \quad (4.2)$$

For Design A, an average butt height of 15mm was achieved that amounted to 1.2 $t.ha^{-1}$ left infield. That relates to a rand loss incurred of $R210.ha^{-1}$. It was lower then the average for manual cutting of 20mm which results in a loss of $R279.ha^{-1}$. This was acceptable but is unattainable if the cane is planted in furrows and the correct field lay out would have to be done to cut at an average of 15mm.

WEAR

Figure 4.8 shows blades hardened to 45 Rc that had worn for 20 min on the left to 60 min on the far right after harvesting approximately 2.1 tons. The type of soil and height of cutting had the most influence on the rate of wear. Clay/humous soils caused less wear compared to gravels and sands. The wear in Figure 4.8 was in a clayey soil.

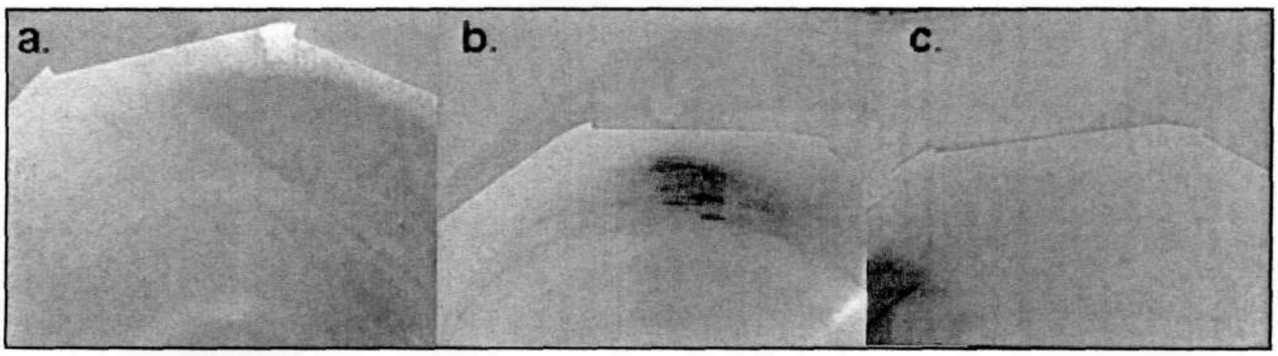

Figure 4.8 Wear on 2.8mm thickness Design A after (a) 20 min, (b) 40 min and (c) 60 min

Two thicknesses were tested, 2mm and 2.8mm. On average the 2 mm thick blades lasted 31 min before reaching a state seen in Figure 4.9 while the 2.8 mm thick blades lasted longer at an average of 54 min. The mass loss as a result of wear of the 2 mm and 2.8 mm blades can be seen in Table 4.1 and Table 4.2, respectively. These results show that there are fast rates of wear initially that decreases as the blade dulls. The thicker 2.8 mm blades lasted on average 23 min longer and had slower rates of wear of 1.15 $g.min^{-1}$.

Table 4.2 Loss of mass for the 2 mm blades at 45 Rc after 20 min and after an average of 31 min when the blades were replaced

	New	20min	31min
TOTAL MASS (g)	1205	1172	1164
Mass Loss (g)	0	33	41
Mass Loss per minute	0	1.65	1.32

Table 4.3 Loss of mass for the 2.8 mm blades at 45 Rc after 20 min and after an average of 54 min when the blades were replaced

	New	20min	54min
TOTAL MASS (g)	1750	1722	1688
Mass Loss (g)	0	28	62
Mass Loss per minute	0	1.4	1.15

The amount of wear deemed it impossible to re-sharpen or re-use the blades and the fast rate of wear was unacceptable due to the costs of manufacturing the blades and the downtime caused by continually changing blades. Appendix B shows the blades' wear under various conditions.

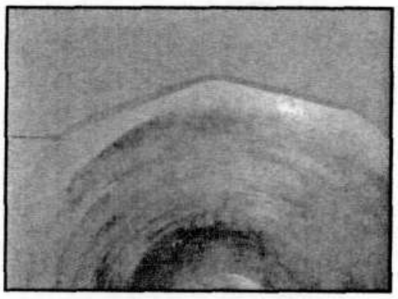

Figure 4.9 The condition of the blade at the point when it was deemed to be ineffective for cutting sugarcane

The hardness was increased to 52 Rc but there was no significant reduction in wear. Other metals were also tried but again there was no tangible improvement in wear and the extra cost for the exotic metals did not justify the slightly longer lasting blade.

SAFETY

Design A offered good safety aspects. It was not an aggressive blade that created any kick back with the machine. The blade did not generate large amounts of dust and debris and the operators felt comfortable with the smooth operation. It was, however, still advisable to wear shin guards and safety boots.

4.4.2 Design A: Limitations and recommendations

The blade needed four modifications; (i) the number of edges, (ii) selection of the surface for sharpening and (iii) the mass. These changes would then require further testing to evaluate their effectiveness.

Tests showed that cutting only took place on half of the blade edge as seen in Figure 4.10. By doubling the number of sides it would result in less wear since there would be more cuts per revolution. The angle of 22.7 degrees would be maintained, but there would be 20 sides.

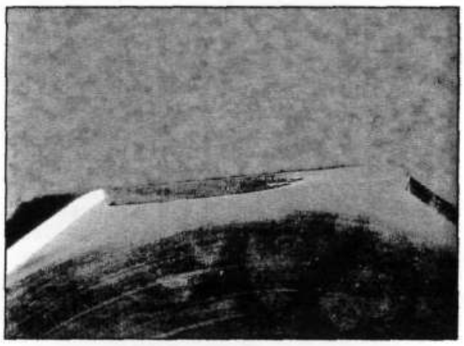

Figure 4.10 Blade edge illustrating only half the edge being worn

Ideally blades should last longer and cost less. Since only the outer edge was used it resulted in a large area of wasted metal each time that the blade was changed. It was decided to design replaceable edges so that the majority of the cost, being the main plate could be re-used.

The sugarcane had a tendency to rest on the blade after it had been cut. This hindered further cutting into the stool, especially wide stools (>45 cm) and caused the engine to strain. One solution to this was to weld ridges on the upper surface that would deflect the stalks off.

To obtain the closest cut to the base of the stalk it was decided to cut with the lower edge. There was, however, an energy requirement to lift the cane stalk up onto the blade edge once cut. The height to lift the cane was the thickness of the blade (2.8 mm or 2 mm).

The last problem was that the mass of the blade was too high at 1.75 kg for the 2.8 mm blade. This caused the engine to labour and the gearhead to slip off the drive shaft. An attempt was made to reduce the mass to that of a conventional blade. To achieve this, holes were drilled in the blades and the thickness of the blade was decreased.

4.5 Blade Design B

Using the information from Design A it was decided to design a 20-edged blade illustrated in Figure 4.11. The design was split into two parts: (i) 20-edged blade with the 22.7 degree cutting angle and (ii) 20-edged blade with a 30 degree cutting angle. The determining factor for these adaptations is to limit the rate of wear. The same material as Design A was used and the Rockwell was taken to 45 Rc. The weight was not decreased due to reducing the cost of manufacturing until a decision had been reached on the blades effectiveness to cut cane.

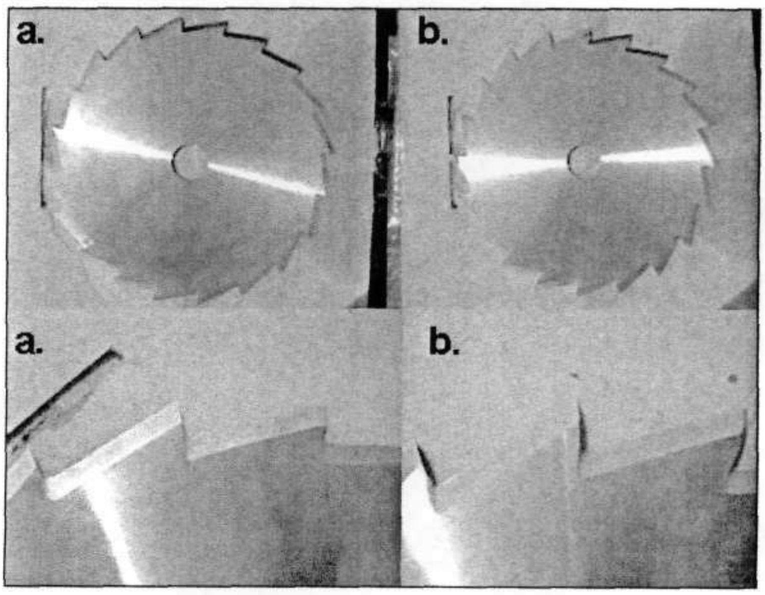

Figure 4.11 Design B (a) 20-edged 22 degree slicing on the left and (b) the 20-edged 30 degree slicing on the right

The edges were also sharpened on the opposite sides so that less energy was required to lift the sugarcane. Using Equation 4.1, the power required for the 20-edged 22 degree slicing blade was 3.5 kW and for the 20-edged 30 degree slicing blade was 4.6 kW. The power of the machine was therefore under-rated for these blades, but was felt to be sufficient for testing purposes.

4.5.1 Design B: Results and discussion

Both blades failed and were inadequate when harvesting sugarcane. Certain aspects regarding these blades are discussed below.

CUT QUALITY

The quality of the cut was similar to Design A and there were no visible differences between the 22-degree and the 30-degree blade. The damage score range was between one and two for both the designs.

HEIGHT OF CUT

The blades were more aggressive due to the extra cuts per revolution. This resulted in kick back and the operators having difficulty controlling the machine. The lack of control resulted in a higher base cut at approximately 26 mm. Using Equation 4.2, resulted in a loss of 2.1 $t.ha^{-1}$ that relates to a monetary loss of $R347.ha^{-1}$ which was regarded as unacceptable.

WEAR

The main reason for changing from Design A was to reduce the wear, however the wear rates remained too high. Figure 4.12 shows the wear after 20 min. The rate of wear was higher than Design A and can be seen in Table 4.4. The 30 degree blade had a lower rate of wear, which was attributed to the greater degree of impact cutting and less slicing. This is due to the edge of the blade using fewer cuts to sever the cane stalks.

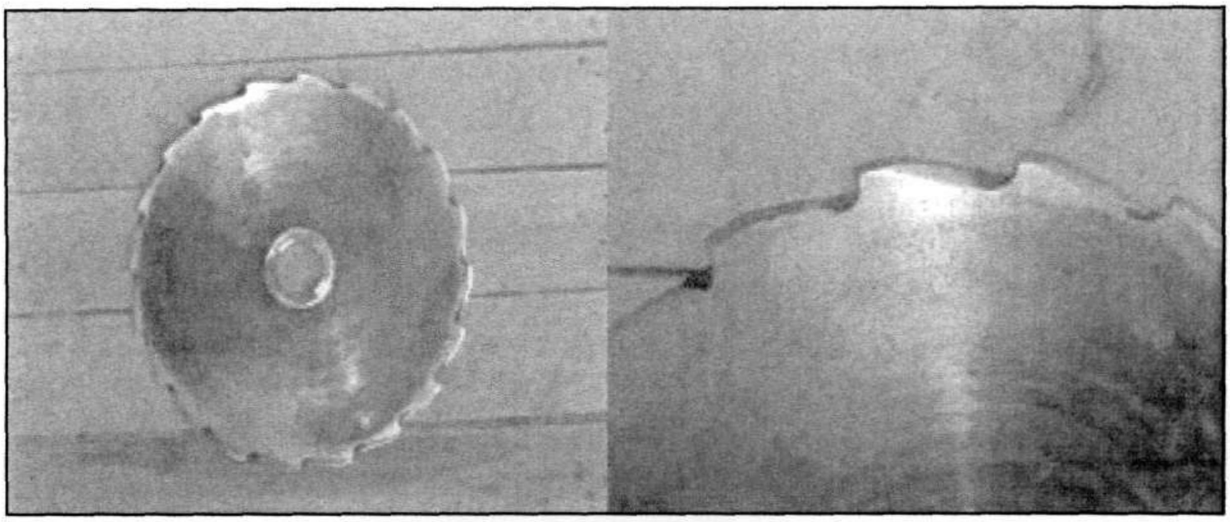

Figure 4.12 Wear after 20 min of operating on the 20-edged 22 degree blade

Table 4.4 Mass loss and rate of wear for 22-degree and 30-degree blade

	22 degree 2.8mm		30 degree 2.8mm	
	New	20min	New	20min
TOTAL MASS (g)	1770	1680	1750	1700
Mass Loss (g)	0	90	0	50
Mass Loss per minute ($g.min^{-1}$)	0	2.25	0	1.25

SAFETY

Both the 22 degree and 30 degree blades performed similarly in a safety assessment. The blades caused kick back and the operators found it difficult to control the machine due to severe vibrations. The noise was significantly higher compared to Design A and was due to double the number of cuts per revolution. This increased the operators discomfort and unease.

4.5.2 Design B: Limitations and recommendations

The recommendation was to discontinue Design B and rather revert back to Design A and try other modifications. It was noted though, that doubling the number of edges increased the use of the cutting edge to from 50 % to approximately 75 % as seen in Figure 4.12. Table 4.4 shows that increasing the blade angle did decrease the rate of wear which could be a design possibility.

4.6 Blade Design C

Design C investigated replaceable blade edges (120 mm x 50 mm x 1.8 mm) as seen in Figure 4.13 with two connection points connected to the main base plate.

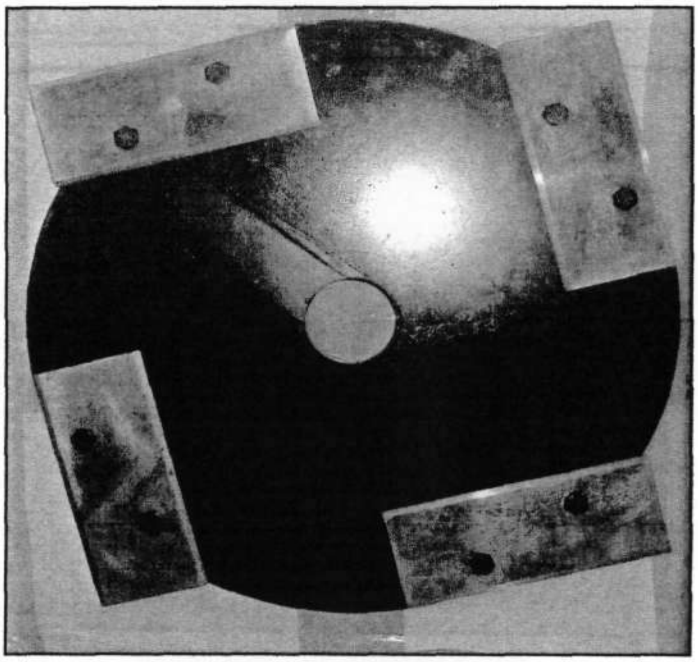

Figure 4.13 Bottom view of Design C with replaceable edges, cutting in a clockwise direction

The number of blade edges had to be reduced from 10 in Design A to 4 due to space limitations. This reduction in the number of edges caused a reduction in power required to 0.69 kW. The FS 500 was therefore overpowered and although it would have been possible to use a smaller brushcutter, it was felt that the smaller brushcutters were not robust enough and would break under the harsh working conditions.

The cutting angle of the blade was maintained at 22.7 degrees but because of fewer blades there was a larger leading edge. This allowed for more wear before loosing the cutting efficiency. The replaceable blades could be used for 2 cuttings, one on each side. The main base plate did not require regular changing, unlike the edges. The edges also did not require laser cutting and could be manufactured more easily and cheaply.

A number of blades were tested, the replaceable blade edge thicknesses were made of both 1.8 mm and 2.0 mm and the edge angle (fineness) was tested at 45 degrees and 24 degrees. From Chapter 3.4, Chancellor (1958) showed that the most efficient fineness was at an angle of 24 degrees. Any angles smaller then 24 degrees were subject to rapid wear and dulling. A 45 degree was also tested due to the rapid dulling of the blade. The rapid dulling did not warrant the 24 degree sharpness that was difficult to obtain. The hardness of the replaceable blades ranged from 42 Rc to 52 Rc. Testing the replaceable blades of the various hardness's was a major safety concern and procedures were put in place to ensure that safety risks were kept to a minimum. There were also a number of modifications within Design C relating to the type of connectors and overall mass of the blade.

4.6.1 Design of connectors

Three different types of connectors were tested. The first was a standard metric size 10 locktite nut and bolt as seen in Figure 4.14. To get the closest cut to the ground and limit the damage done to the cane, the bolt head was inserted at the bottom of the plate.

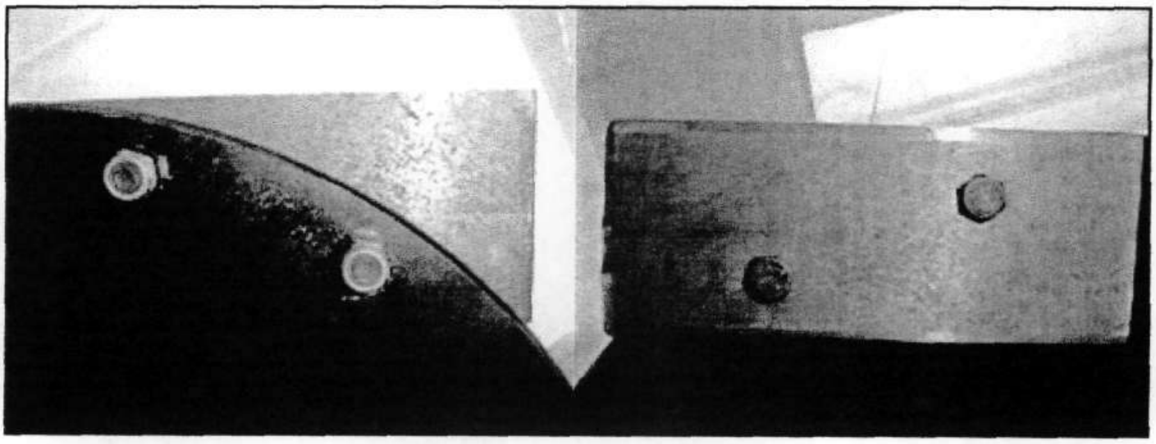

Figure 4.14 Top (left) and bottom (right) view of the bolt connectors on the plate

The second connection type was a rounded bolt with an allen key head as seen in Figure 4.15. The nuts were originally welded to the bottom of the plate, but after some testing it was decided to cut the threads into the plate and then to harden the plate. The head was positioned at the top of the plate to allow for the closest possible cut with the least amount of damage to the cane stools. Spring washers were inserted to stop the bolts loosening due to the vibrations.

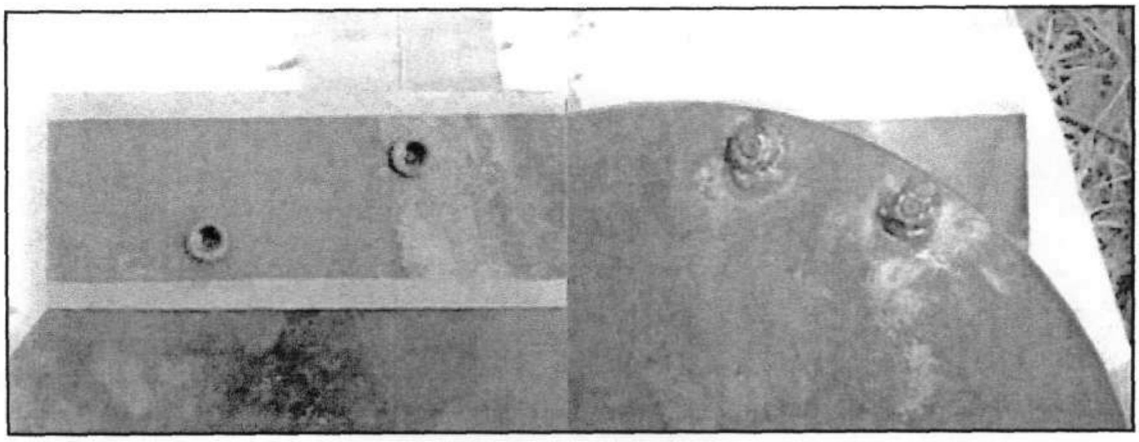

Figure 4.15 Top and bottom view of allen head connectors

The final connector design was a tapered allen key head. This was to offer the least amount of resistance when cutting and to reduce the damage to the cane stools. Figure 4.16 shows the connector in the assembled and un-assembled state.

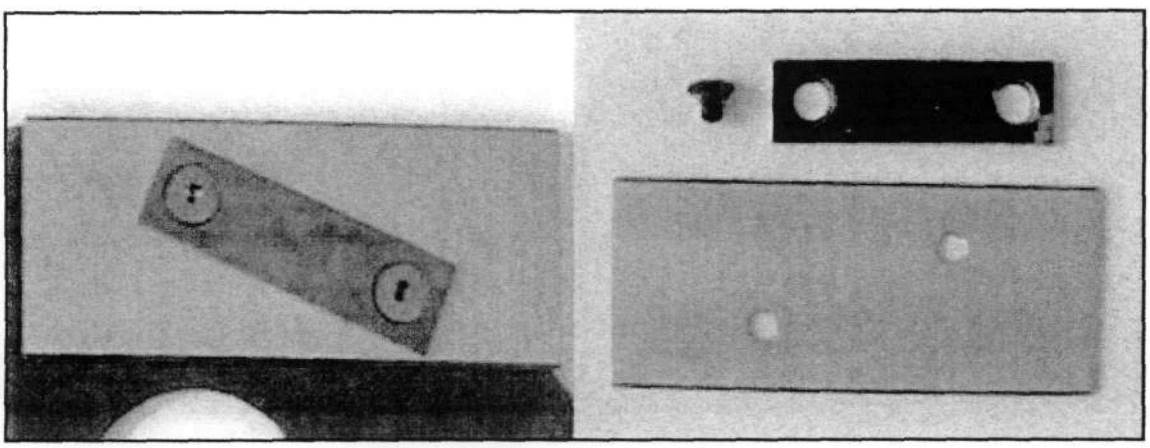

Figure 4.16 Top view (left) and unassembled state (right) of the counter sunk connectors

4.6.2 Mass

Mass became a significant issue with the replaceable blades design and different ways to reduce this were assessed. The thickness of the main base plate was reduced from 2.8 mm to 2.4 mm but with the threaded design there was insufficient thread to hold the blades securely. The other method used to reduce the mass was by drilling four 50 mm diameter holes into the base plate, as seen in Figure 4.17 that reduced the mass by 200 g.

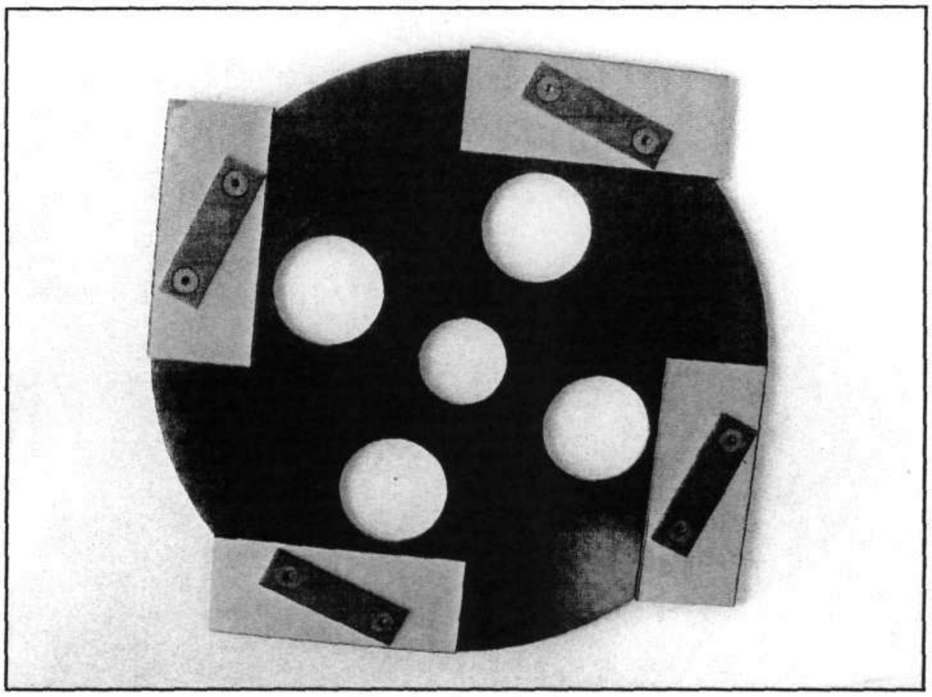

Figure 4.17 Base plate with four holes drilled to reduce the blade's mass by 200g

4.6.3 Design C: Results and discussion

Design C proved to be an improvement. It began to meet some of the requirements within the design constraints. These included cutting the cane satisfactorily and manufacturing the blades at a reasonable cost.

CUT QUALITY

The quality of the cut was slightly lower than Design A. This was expected because of fewer cutting edges. There was a tendency to cause damage up to a class 6, but on average the damage was at 2, which was assumed acceptable. Figure 4.18 shows the variance of the damage caused. The damage circled in red has a damage rating of 4, while the yellow circle shows a damage rating of 1. This variance could be explained by the change in speed during the movement of the cutter as it is swung through the cane. Another cause might be that the higher damage could have been cane partially cut during the first sweep and a second sweep was required to complete the cut. Another factor contributing to the damage was the type of connectors. The bolts sat proud and caused more damage by shredding the stools unnecessarily after the cane had been cut. However, the final connector design where the thread was cut into the plate reduced this problem.

Figure 4.18 Damage of the cane caused by Design C. The red circle shows a damage rating of 4, while the yellow circle shows a damage rating of 1

HEIGHT OF CUT

The blades were slightly more aggressive due to a larger cutting edge. This, combined with the connectors lifting dust and debris, caused the operators to not always see the base of the cane. It resulted in a slightly higher base cut at approximately 17mm, compared to Design A. This resulted in a loss of 1.4 $t.ha^{-1}$ and a monetary loss of $R238.ha^{-1}$. This was regarded as acceptable and should improve if the field was prepared for the specific harvesting operation, such as not planting in furrows.

WEAR

The rate of wear was similar to Design A, but due to the larger leading edge it could be used for longer periods. The wear can be seen in Figure 4.19. These blades were hardened to 45 Rc and operated in sandy soils for 64 min after harvesting approximately 3.8 tons.

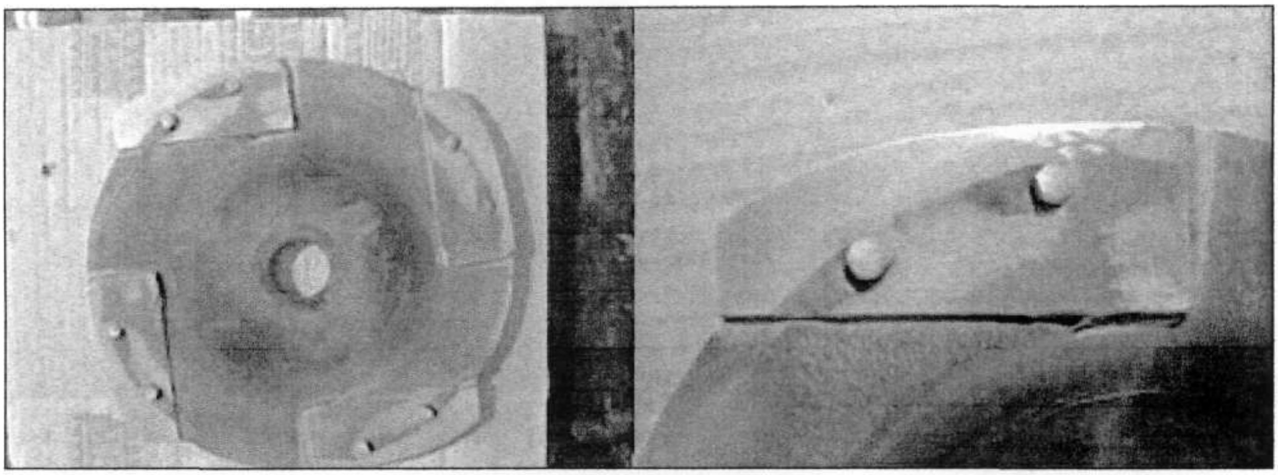

Figure 4.19 Wear of Design C. Blades hardened to 45 Rc after operating for 64 min

The rate of wear was lower compared to Design A and is summarised in Table 4.5. A total mass loss of 56 g was lost before replacing the blades. This occurred after working for two hours and after harvesting approximately 6.5 tons. This was a marked improvement from Design A. The blade hardness was increased gradually for safety reasons, but it was seen that blades in the range of 45 and 50 Rc wore at similar rates.

Table 4.5 Mass loss and rate of wear for Design C with replaceable blades

	New	1 Edge Used	2 Edges Used
TOTAL MASS (g)	1552	1515	1494
Blade Mass Loss (g)	0	36	56
Blade Mass Loss per minute ($g.min^{-1}$)	0	0.72	0.47

The two fineness angles of 24 and 45 degrees were also tested but results were inconclusive. There were no visible differences with regard to rate of wear or cleanness of cut. It is noted that the wear took place at such a high rate that after 10 min the fineness was no longer a factor.

CONNECTORS

The connectors mentioned above were tested and the allen key heads (Figure 4.15) performed the best. The bolts with the bolt heads wore down to such an extent that it was impossible to change blades without cutting the bolts (Figure 4.19). Another disadvantage was that they caused excessive damage to the stool and the cut cane. The tapered allen key heads did not have enough thread and continually pulled out and stripped the thread. Therefore, the proud allen key heads were selected as the best connector.

SAFETY

For Design C, safety became critical because of the nature of the detachable blades. It was noted that the hardness should not be taken above 50 Rc. Figure 4.20 shows shattering that took place at 52 Rc after the blades hit a rock in the field. This was not only a safety risk, but the unbalancing of the blade also caused damage to the drive shaft of the brushcutter.

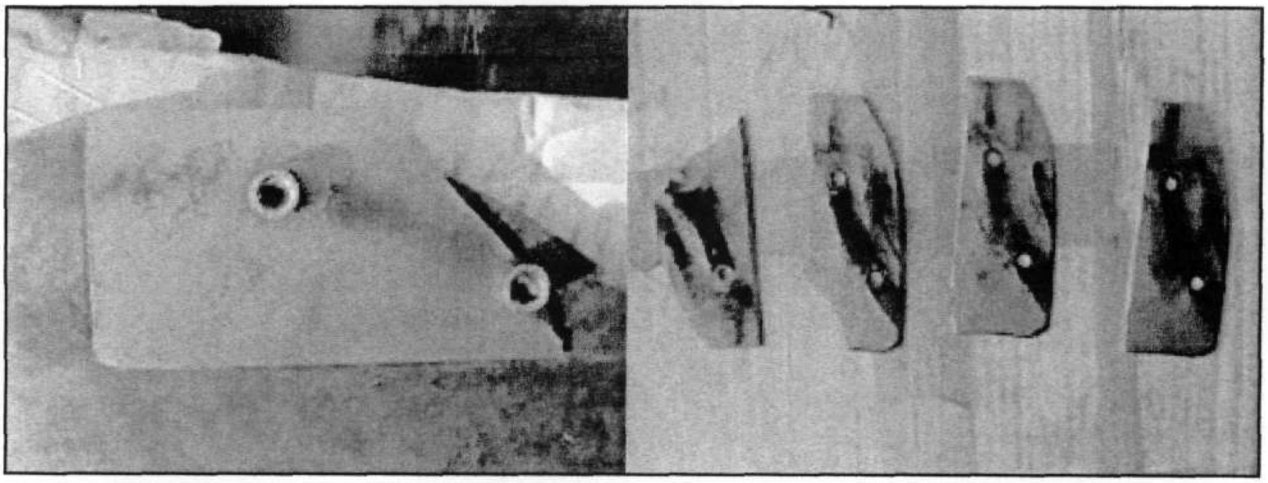

Figure 4.20 Shattering of blades hardened to 52 Rc as a result of hitting a rock

At lower Rc values (46 and 48) the blades were more likely to bend. This caused some connectors to break when hitting a large rock. A test was done with blades at 45 Rc in a controlled environment. When the blade hit a rock it did not shatter but rather bent the blades (Figure 4.21) and sheared the connectors. This was more favourable because when a bolt is sheared the blade remained attached and swung away as seen in Figure 4.21. The blade was useless once it hit a rock, unlike Design A, therefore, it was advisable to be careful in rocky conditions. Depending on the skill of the operator the majority of the rocks should be moved before cutting takes place.

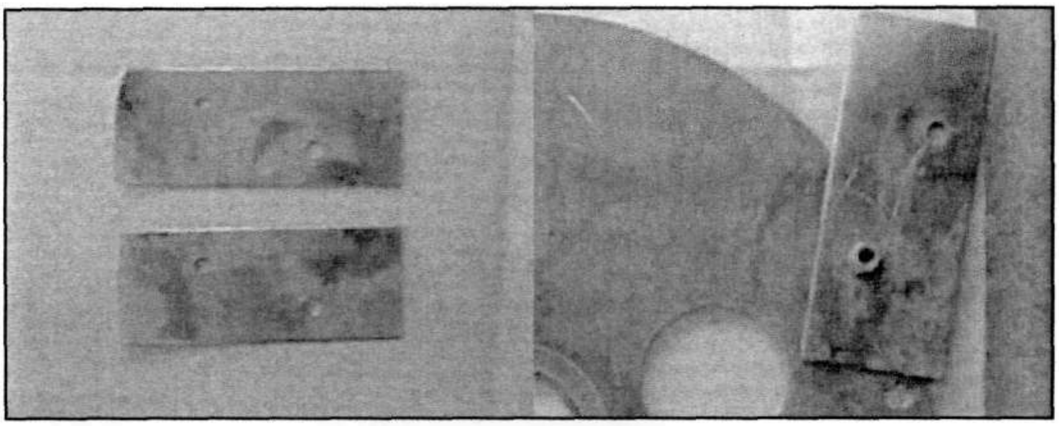

Figure 4.21 Blades of 45 Rc that underwent a shatter test in a controlled environment showing only the connectors breaking

The connectors generated extra debris and dust that affected the operator adversely. The operator thus required goggles and a face mask to stop the dust hampering his ability. Tests showed that blades that become detached flew away from the operators and care had to be taken to ensure that no persons were in front of the operators.

4.6.4 Design C: Limitations and recommendations

Design C met more of the constraints outlined at the start of the chapter. The quality of cut, height of cut, mass and safety had to be compromised slightly in order to become economically viable. Limitations were that (i) only two blade edges were usable, (ii) the connectors pulled out and stripped the plate, (iii) debris was forced in between the blade edge and main plate and caused it to bend, (iv) the blade was still too heavy, (v) the rate of wear was still a concern and (vi) the efficiency of the system was influenced by rocks in the field.

It was hence decided to adapt the design to allow four edges to be used instead of two. This would enable the blades to operate for up to 4 hours before requiring replacement. It was decided to change the shape of the replaceable blades from a rectangle to a square to allow for 4 changes.

The connectors continually pulled out and broke. An extra connector was hence added to give more strength and the plates were hardened to between 48 and 50 Rc. This was not a cause for safety issues since the main base plate never experienced high impacts or shattering. The harder plates however strengthened the threads enabling them to withstand more abuse and to rather strip the bolts allowing the plate to be reused.

A concern was that debris was forced between the replaceable edges and the main base plate during operation and caused the replaceable edges to bend up and consequently shear the bolts (Figure 4.22). The arrows clearly point out where the debris, mainly consisting of sugarcane trash and soil, accumulated. To alleviate this problem the replaceable edges were made slightly thicker so that they could not bend easily, however mass was a concern. It was also decided to chamfer the edges to deflect the debris over the blade and not collect under it.

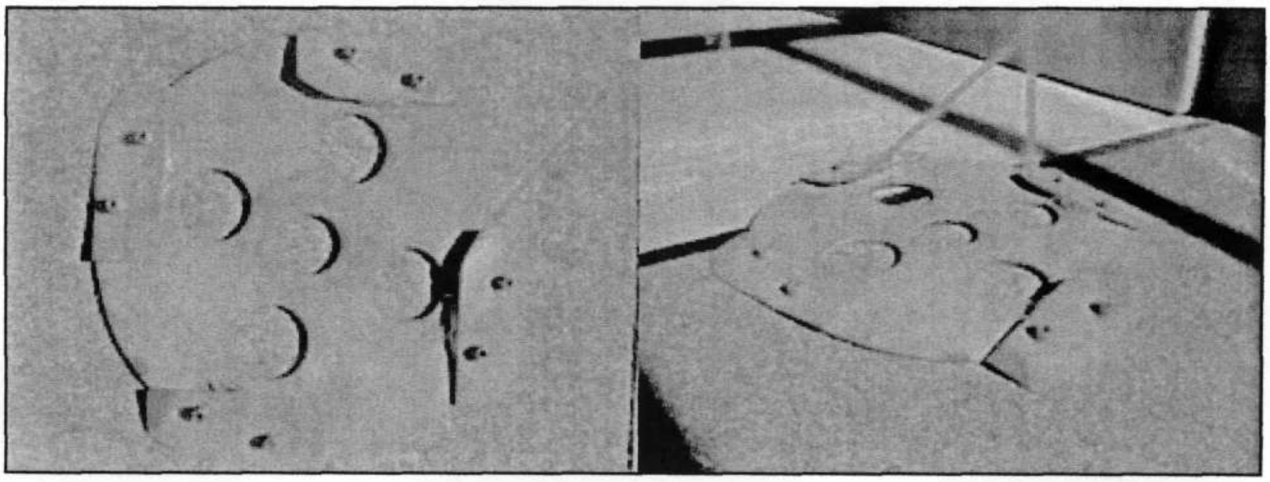

Figure 4.22 Design C showing debris forcing the replaceable edges away from the main base plate

4.7 Blade Design D

This was the final design and performed the most satisfactorily. Design D had replaceable edges but was a larger replaceable blade compared to Design C. The plate was identical but the replaceable blades were increased to 100mm x 100mm x 2.8mm with three connection points as seen in Figure 4.23 (detailed drawings can be seen in Appendix A). The cutting angle was increased to 45 degrees to apply more impact and less slicing. The angle of 22.7 degrees performed satisfactorily but the wear was too great. Increasing the angle creates a larger cutting edge and allows for a longer life span. These changes were made to allow more usage from the blade. The life of the blade was also increased by making it thicker so that it could be safely hardened to 48 Rc and have more of an impact cut that results in fewer cuts per stalk. Other changes included the chamfering of the blade edge down toward the plate to stop debris collecting between the replaceable edges and the main base plate, and attaching the replaceable edge more firmly to the plate with the extra connector. The connectors were allen key heads that screwed directly into the plate that had been hardened to 48 Rc. The allen keys included spring washers to stop them from loosening due to vibrations.

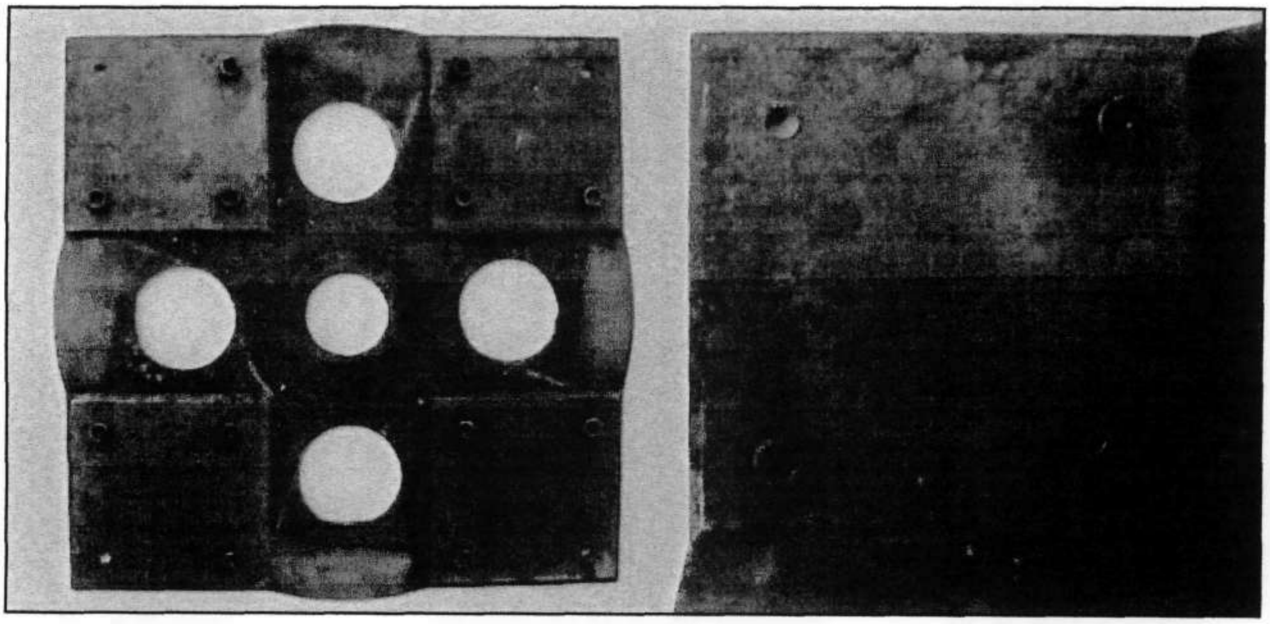

Figure 4.23 Design D with 4 replaceable edges with a 45 degree cutting angle and fastened with three connection points

The power required changed due to the cutting angle. Using Equation 4.1 showed that the power required was 1.4 kW which is under the design specifications of the FS 500 model.

4.7.1 Design D: Results and discussion

The blade performed satisfactorily and proved to be the best compared to the other designs. Results have been split into three aspects, namely, cut quality, height of cut, wear and safety.

CUT QUALITY

The cut quality was satisfactory and lay between 1 and 3 with an average of 2.1. Figure 4.24 shows cane that was cut using Design D. The green circled cut cane had a damage rating of 1, the yellow had a damage rating of 2 and the red circle had a damage rating of 3. It was noted that the damage increased as the blade dulled. The cut quality could be a good measure of when it is time to replace or rotate the blades. As soon as the damage rating rose above three it was an indication that the blade was blunt or the motor was laboring and needed a filter change.

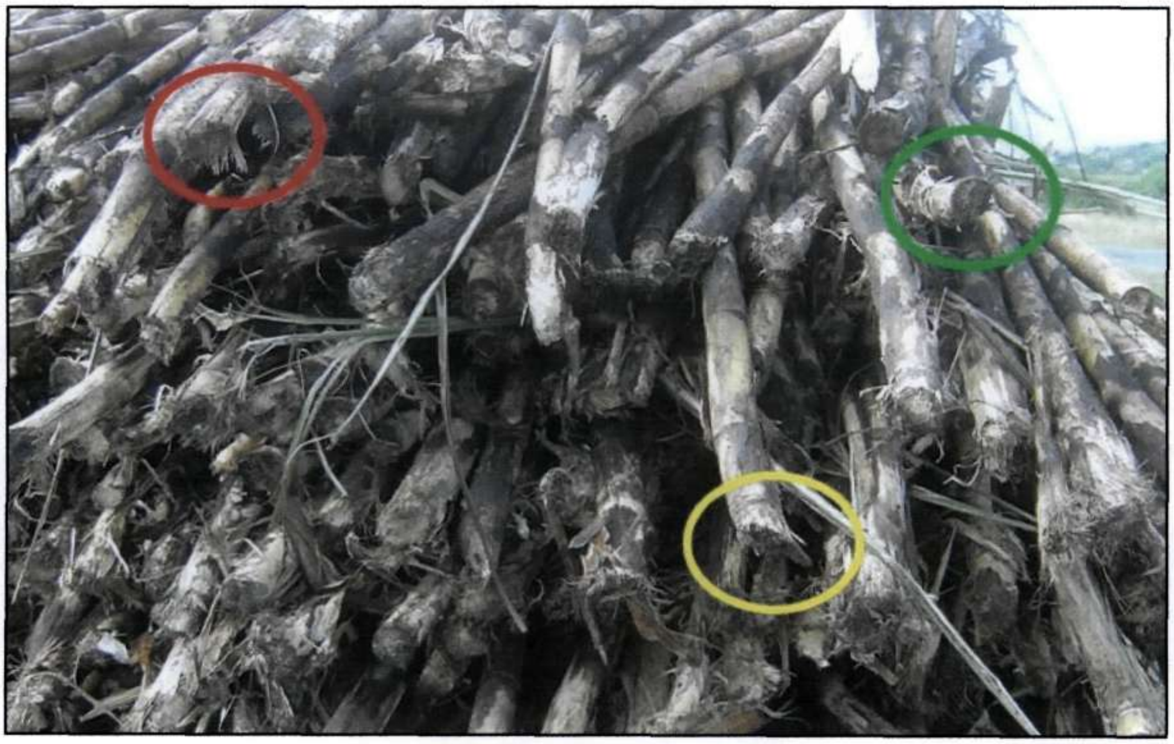

Figure 4.24 Damage to the cane caused by Design D, the green, yellow and red circles showing damages of 1, 2 and 3, respectively

HEIGHT OF CUT

The blades were slightly more aggressive due to the larger cutting edge and the larger cutting angle of 45 degrees. There were still large amounts of dust and debris, but with the correct cutting aids (goggles) it was possible to cut close to the ground level. An average of 18 mm of butts was left above the ground. It resulted in a loss of 1.5 $t.ha^{-1}$ and a monetary loss of $R251.ha^{-1}$. This was acceptable and will improve if the land is prepared for the harvester, i.e. not planted in furrows.

WEAR

The rate of wear proved to be the lowest of the three designs. This, combined with 4 usable edges contributed to a blade that could harvest for over 4 hours and harvest 16 tons before the blade had to be discarded. The wear can be seen in Figure 4.25, starting with a new blade on the left, followed by 40 min, 122 min, 215 min and 305 min respectively. On average one edge lasted 80 min before it had to be changed. Design D had the best performance with regard to the rate of wear. Appendix B shows outlines of blades operating under various conditions.

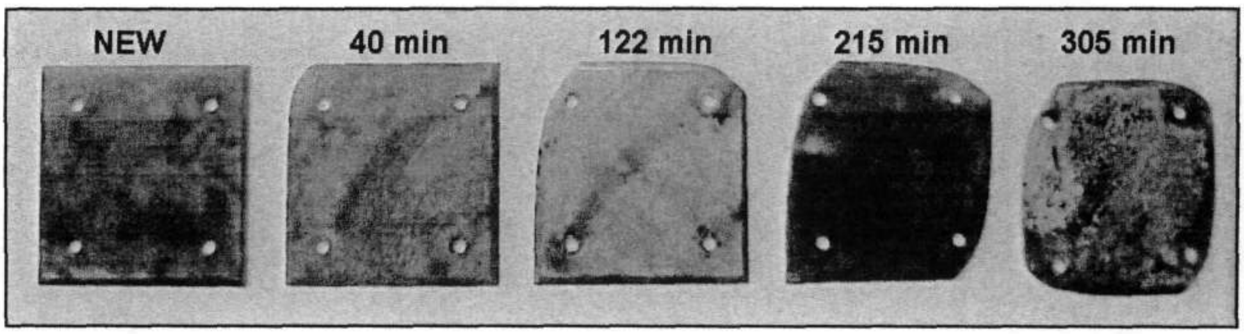

Figure 4.25 Wear of Design D starting from new on the left, after 40 min, 122 min, 215 min and 305 min respectively at an average mass loss of 0.42 $g.min^{-1}$

The rate of wear was found to be the least and could mainly be attributed to the thickness of 2.8 mm combined with the hardness of 48 Rc. The rates of wear can be seen in Table 4.6, with the final rate of wear being 0.42 $g.min^{-1}$. The rate of wear was high compared to conventional chopper harvester blades that wear at a rate of 0.04 $g.min^{-1}$ (Chapter 3.5) but compared to the floating chopper harvester (Chapter 3.5) it wears 40 times faster. This could be expected due to the chopper harvester blades rotating at 600 rpm, compared to the brushcutter rotating at 6000 rpm. The total mass of the blade was still high with a maximum of 2.1 kg and a minimum of 1.9 kg.

Table 4.6 Mass loss and rate of wear for Design D with replaceable blades

	New	1 edge used	2 edge used	3 edge used	4 edge used
Total Mass (g)	2055.44	2025	1988.4	1948	1919.7
Time (min)	0	78	154	231	308
Blade Mass Loss (g)	0	28	62.4	100	128
Blade Mass Loss per minute ($g.min^{-1}$)	0	0.36	0.41	0.43	0.42

SAFETY

The safety was better then Design C. This was mainly due to the extra connector and the attachable blades being thicker and hence where not prone to shattering or bending. The blades, however, had become detached and had been flung up to 10 m away. The more aggressive blade did highlight the need for protective clothing. That includes: shin pads, steel capped boots, overalls, goggles, masks and ear muffs. Design D operated for approximately 120 hrs without any injury, but this is no reason to disregard strict harvesting rules and regulations that should reduce the risk of injury. Care must be taken in changing and rotating the replaceable blades to maintain the blade balance. This can be seen in Figure 4.26 where the blades are rotated in the same direction ensuring the same orientation for each blade and maintaining the balance of the blade.

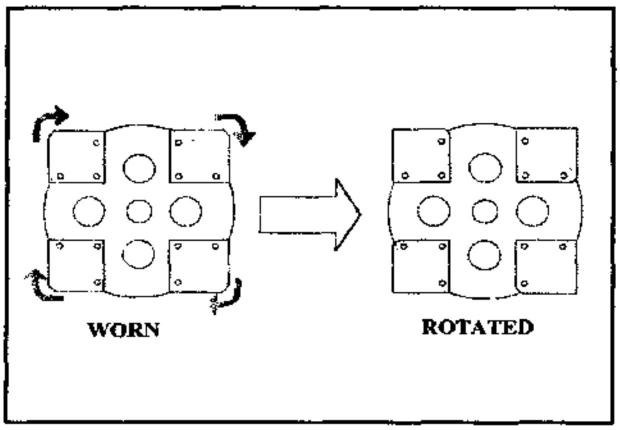

Figure 4.26 Rotating the worn edges ensuring the balance is maintained

4.7.2 Design D: Limitations and recommendations

The main limitation to Design D was the mass of the blade. This caused stress to the drive shaft and caused the gear head to slip off during operation, even with the grub screw inserted (Chapter 4.2.3). Future ways to decrease the mass should include:

1. Reduce the blade's diameter,
2. add or increase the size of the holes, and
3. use lighter material.

The connectors could be adapted to eliminate the allen key bolt heads protruding that caused damage to the cane and excessive dust and debris. The bolts had a tendency to shear when the blade hit a rock, as highlighted in Figure 4.27. The plate then requires having its thread tapped again, which is not an easy task to perform in the field. The shearing of the bolts caused the blade to become unbalanced and resulted in damage to the vibration unit situated between the drive shaft and motor. This can result in the machine breaking its drive shaft. This needs to be addressed by developing specialised connectors,

Figure 4.27 Sheared bolts circled in red that cause the blade to become unbalanced

4.8 Failed Designs

In spite of the desired criteria other commercially available blades were tested in conjunction with the ISH blades. It was not possible to do a full analysis on all the designs attempted. Through the help of specialists, the following designs were tested and were found to be inadequate for harvesting sugarcane mainly due to wear, but also to the inability to cut cane efficiently. The following blades were tested but found to be ineffective (Figure 4.28): Red Devil segmented cutting blade, Avancer turbo cutting blade, 5-star blade, 3-pronged STIHL blade and numerous circular saw blades.

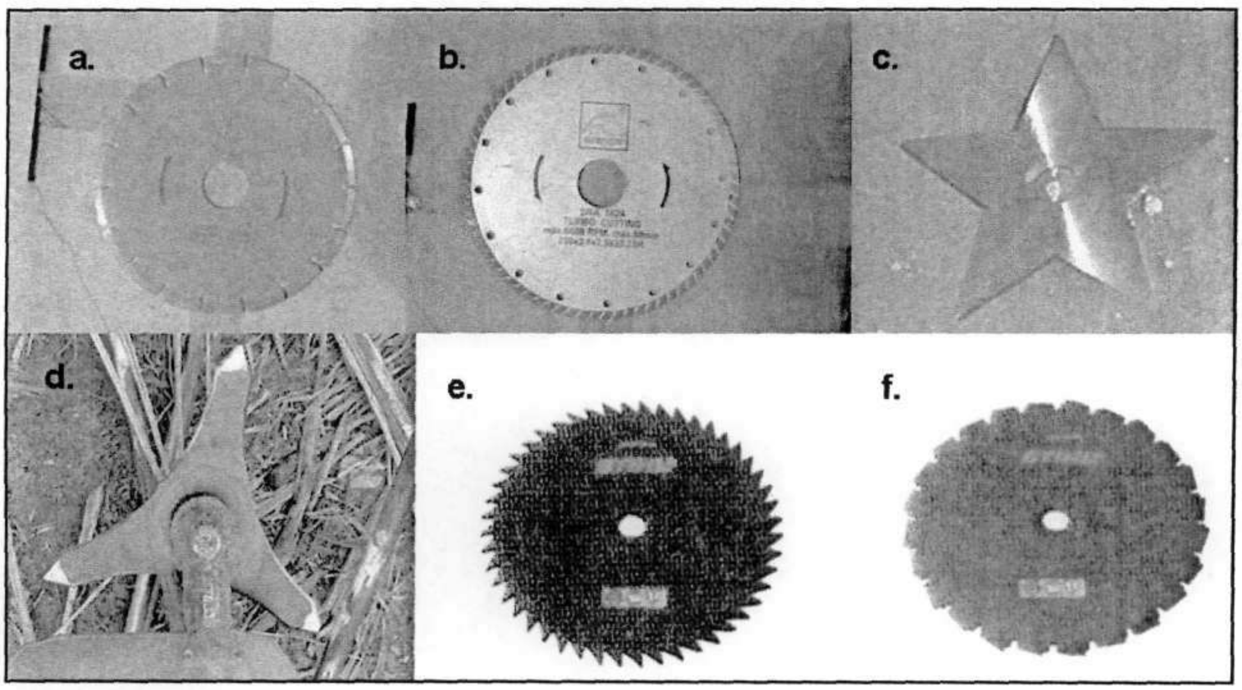

Figure 4.28 Blades that failed to cut cane effectively, (a) Red Devil segmented cutting blade, (b) Avancer turbo cutting blade, (c) 5-star blade, (d) 3-pronged STIHL blade, (e) and (f) 2 circular saw blades

4.9 Conclusion

Blade Design D was found to be the best blade with respect to most of the criteria. It has 4 replaceable blades that are connected using allen key bolts onto the main base plate. A summary comparing the blades can be seen in Table 4.7.

Table 4.7 Comparison between the various blade designs

		Thickness mm	Wear $g.min^{-1}$	Time Min	Tons $t.blade^{-1}$	Losses $R.ha^{-1}$	Damage 1 to 12	Safety	Mass g
Design A		2	1.32	31	1.5	210	1.16	Excellent	1205
		2.8	1.15	54	2	210	1.16	Excellent	1705
Design B	22 degree	2.8	2.25	Na	na	347	1.5	Poor	1770
	30 degree	2.8	1.25	Na	na	347	1.5	Poor	1705
Design C		2	0.47	128	6.5	238	2	Average	1552
Design D		2.8	0.4	308	16	251	2.1	Average	2055

The determining factor was the tons cut per blade due to the cost of manufacturing. Design D had the greatest at 16 $t.blade^{-1}$ and showed the lowest wear of 0.4 $g.min^{-1}$. The main limitation was the mass and it still wore too quickly; therefore, research is required to make the blade lighter and more durable. This is a working design and is suitable, but not optimal. After a suitable blade was designed it was still necessary to implement a successful system that could operate under various conditions and perform at a productivity level higher than the conventional manual harvesting method. Due to the substantial input to the project by Illovo Sugar it was decided to name the new cutter the “Illovo Sugarcane Harvester”.

It was anticipated that designing a harvesting system would be difficult because of people’s attitudes, resistance to change and personal preferences. Part B containing Chapters 5, 6 and 7 was devoted to the formation of a suitable harvesting system and the evaluation of the impact on the human body.

PART B: SYSTEM AND ERGONOMIC ANALYSIS

5. SYSTEM ANALYSIS

Once the blade and machine (Illovo sugarcane harvester) were produced, a system was required to enable the operators to harvest sugarcane efficiently. It was also necessary to implement the system smoothly within the rest of the supply chain. The system included from the field being burnt for harvesting to transporting the cane to the loading zone. Illovo Sugar offered to provide assistance in terms of location, manpower and management and it was therefore decided to test the system in their Sezela Mill area.

5.1 Introduction

The current system used on the Illovo farms on the South Coast is shown in Figure 5.1. Cane is cut and stacked manually into 4 ton bundles. Bundles are then winched onto side loading trailers where they are weighed on an automatic weigh bridge and finally dumped on the loading zone. Once on the loading zone, the cane is loaded onto inter-link vehicles using Bell loaders and then transported to the Sezela mill. The steep slopes restrict the use of chopper harvesters or other mechanical means of loading.

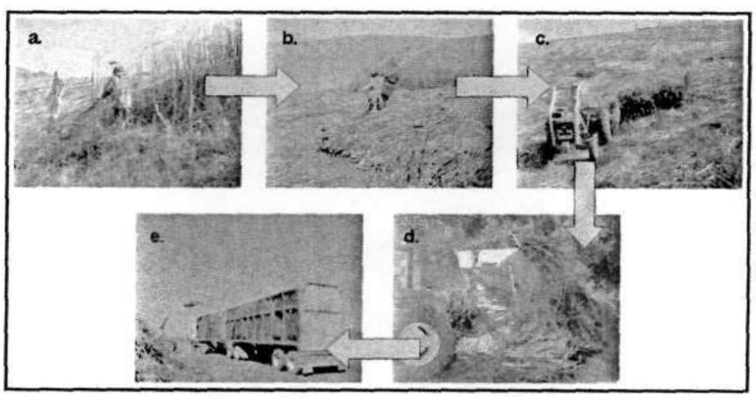

Figure 5.1 System used on Illovo farms on the South Coast that (a), (b) cut and stack, (c) load onto side loading trailers, (d) transported to the loading zone by tractor where dumped and (e) a bell loader loads the inter-link vehicles

5.2 Aims and Objectives

The system analysis included designing the most efficient method of incorporating the "Illovo sugarcane harvester" into the current system of transportation. An analysis was required to determine where the time was spent doing the various actions, what the rate of harvesting was under various yields and conditions and how much the system would cost.

The objectives were split into many aspects that are listed below:

1. Design a system that would fit into the current harvesting and transportation system,
2. ensure safety at all times,
3. increase productivity and profitability,
4. ensure machine durability and
5. operate on steep slopes.

5.3 Methodology

Measurements were taken during the 2005 and 2006 harvesting season. The 2005 results were taken from harvesting on Isonti farm, Umzinto and the 2006 results were taken off Esperanza farm, Umzinto. The results obtained in 2005 were not favourable due to teething problems, a steep learning curve and the operators training and practice. The system was adapted slightly in 2006 and showed a marked improvement. The system development followed an incremental change approach. The human body knows its limitations and how to find the easiest and most efficient method of performing a task. The operators where, therefore, given guidelines on an operation, but were allowed freedom to change the system as seen fit. The biggest issue was to ensure that the safety standards were not jeopardised. Proper supervision helped to alleviate this issue. The final system developed is explained below.

5.3.1 System Description

Two fully trained operators operated one machine at a time, while two unskilled workers conducted the sorting, topping and stacking. The tasks for harvesting using the ISH were split into two task components: (i) Cutting with the machine harnessed and (ii) pulling with a staff implement or crook. Figure 5.2 illustrates these two tasks.

Figure 5.2 System of harvesting using two operators, the puller uses a staff for pulling the cane over into a windrow (red) and the cutter (yellow) cuts the cane using the Illovo sugarcane harvester

The cutter has the machine securely harnessed around his shoulders ensuring that the clip to connect the machine onto himself is positioned a hands length below the hip bone. The machine needs to be balanced on the harness to alleviate excessive arm strain. The cutting motion was from right to left and the front right leg was placed in front of the left and used as leverage. The machine was then swung back by twisting the torso. One motion cuts approximately 5 stalks, but this depends on the thickness and density. Care was taken to not hit excess dirt and stones, but at the same time to cut as low as possible. Two dominant motions are used: (i) a gentle push through the cane where it cuts gradually and (ii) a faster swipe that uses the machines momentum. The faster swipe motion cut quicker, but was less accurate leaving more butts behind and the blades were more susceptible to damage. According to STIHL SA both motions are acceptable and do not damage the machine and it is purely personal preference which motion should be used.

The staff implement used for pulling the cane over was similar to a shepherds crock. It was 1.5 m long with a 400 mm radius half circle at one end and an enclosed handle at the other. It was made out of 12 mm re-enforcing rod and was used to ensure that the cane falls in one direction forming a windrow. The puller stands alongside, to the left of the cutter to pull cane. The puller needs to pull the cane from above the centre of gravity to ensure no cane sticks fall in the opposite direction and obstruct the cutter. A force must be exerted in the correct direction (left) before the cane is cut to ensure the sticks fall in the correct direction and to help the cutting process. It helps the cutting process by pulling the sticks away and by applying a side force that helps cut the stems. The puller's efficiency was the determining factor with regard to the speed of operation. The puller needs to lay the cane down and gather the next group of stalks to be cut before the cutter pulls the machine back. The cutter was usually forced to wait, but by applying the correct pulling technique this delay can be minimised. The correct technique uses the left wrist and the staff was held loosely with the right hand. The staff was inserted perpendicularly into the line ahead of the cutter, the wrist then twisted and gathered the cane to be cut. This was followed by pulling and applying a side force to aid the cutter as shown in Figure 5.3. When inserting the staff perpendicular before twisting care must be taken to not hit the rotating blade. The puller's other responsibility was to move rocks that obstruct cutting and cause damage to the blade. The rest of the team comprised of two unskilled workers who sorted the cane, topped and stacked the cane for loading.

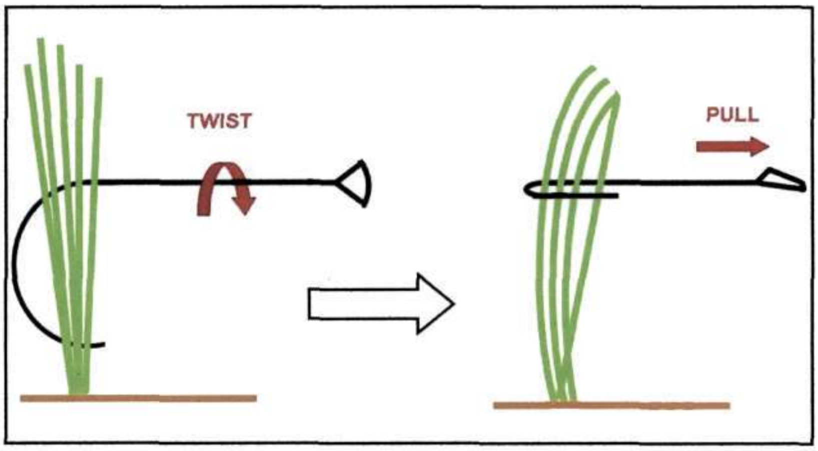

Figure 5.3 The twisting motion using the left wrist followed by pulling the cane with the staff to aid the cutting

The sorters, toppers and stackers followed the machine while cutting and combined approximately three cut lines into a single windrow. They ensured that the tops were aligned and the line was clear so that the operators had a clear pathway for harvesting. Figure 5.4 shows the sorters who pushed the cut windrow (circled in yellow) into a manageable small bundle with their feet and then transfer it to a combined windrow (circled in red). This was then topped and stacked to fit into the current system shown in Figure 5.1.

Figure 5.4 Sorters organising the cut windrow (yellow) and placing it into a combined windrow (red) for subsequent topping and stacking

The Illovo cutter was only able to cut from right to left due to the machine configuration. Cutting in this fashion means that the operators had to cut a row, then walk back and start the next row, this wastes time and energy. Figure 5.5 depicts this, where the green lines are rows of cane, the black arrows show the direction of cutting and the red dashed lines represent walking back to the start of a new line for cutting.

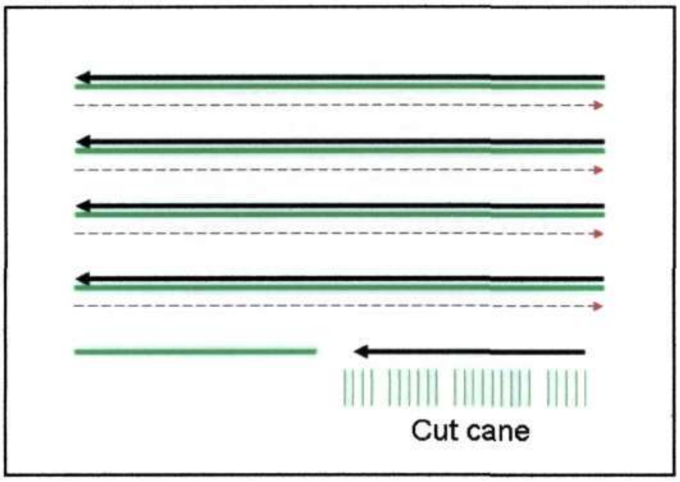

Figure 5.5 Direction of cutting (black arrow) the cane (green lines) and where the operators have to walk back to the start of the next line (red dashed arrow) using System 1

Figure 5.5 depicts System 1 and is used on short lines (< 20m) and on steep slopes (>75%). To save the extra walking (red dashed arrows) a block harvesting system was introduced (System 2). System 2 cuts in blocks that become smaller and smaller and illustrated in Figure 5.6. This was used if the lengths of lines were greater than 20m (optimally 50m) in length. The total number of lines that were cut per block was approximately 15. This would yield an area of 0.075 hectares and at a yield of 60 tons.ha $^{-1}$, there would be sufficient cane to stack a 4.5 ton bundle.

The systems were analysed by performing time and motion studies using the sheets seen in Appendix C. The time and motion studies indicate where time was being wasted (e.g. walking with machine to the start of new line). The system was also analysed using the performance and output per hour that was achieved.

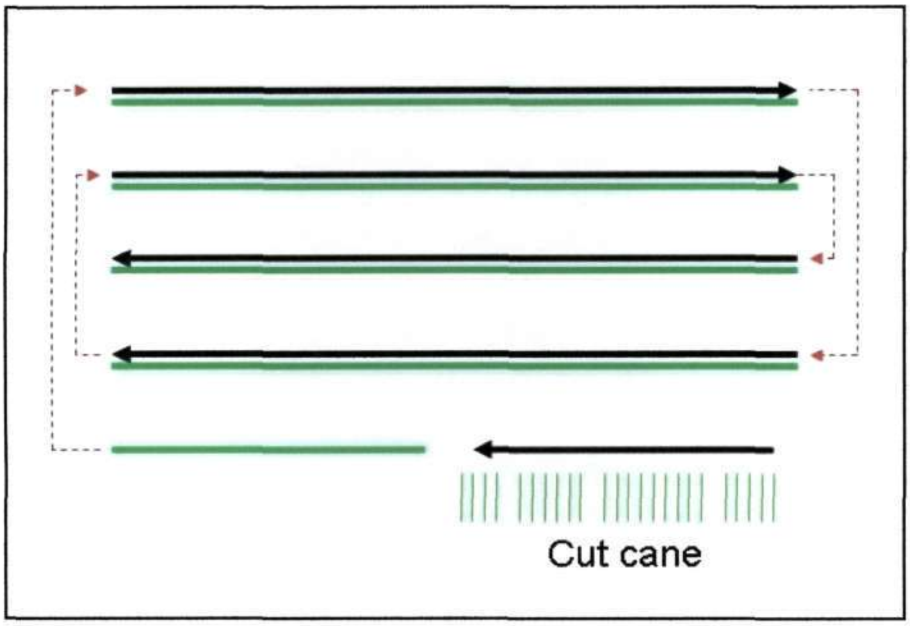

Figure 5.6 Direction of cutting (black arrow) the cane (green lines) and where the operators have to walk (red dashed arrow) using the block method (System 2). This saves time and energy

5.3.2 Safety

The system had to be analysed from a safety perspective. This was achieved by supplying the operators with safety equipment recommended by the suppliers of the machines (goggles, ear-muffs and long pants with safety boots) and observing where problems might arise. An ergonomic study by a team from Rhodes University, Grahamstown was also carried out. Any problems or injuries where also recorded on sheets provided (Appendix C).

5.3.3 Measurements

A foreman was employed to record and take measurements. He was required to fill in the sheets seen in Appendix C. The type of cane and the conditions of the field (stones, slope, and lodging), the time spent in the field, the total time spent operating, fuel consumption and any problems incurred with the machine while harvesting were recorded. From this, it was possible to obtain the harvesting rate during operation and harvesting rate while in-field with respect to tons cut and area cut per hour. Problem areas could also be identified.

From these results it was possible to obtain the productivity and cost of operating under various conditions. This was compared to current manual harvesting systems and recommendations could be made as to whether it was a viable solution for harvesting sugarcane.

The machine had to be observed for its durability and estimate its life to determine the cost of the system. This was done by regularly returning the machines to a recognised dealer who stripped and tested the machines for wear in the rings, loss of compression caused by dust, damage to the gearbox and drive shaft, and wear in the clutch.

5.4 Results and Discussion

5.4.1 System

The block cutting (System 2) was more effective then System 1 in terms of output. A difficulty with System 2 was the first line inside the field, this was difficult to cut and the entry point into the rows was difficult. The puller was required to stand behind the cutter and pull the cane diagonally, which got caught in the adjacent row making it difficult for the sorters (Figure 5.7).

The cane required more sorting (Figure 5.7) but, the increase in efficiency after the first line warranted the system.

Figure 5.7 The first line cut inside the field to start the block harvesting (System 2) that required more sorting and took longer to harvest due to the limited space to operate

Issues arose using System 2 when operating on steep slopes (> 75% or 35°) where it was not possible to harvest in blocks since it required to much energy and strength to cut up-hill (swinging the machine against the gradient) and to pull the cane up the slope (Figure 5.8). There was also an increase in soil contact, compared to cutting down the hill. In addition, the cane tended to slip down the slope into the next line making it difficult for the sorters.

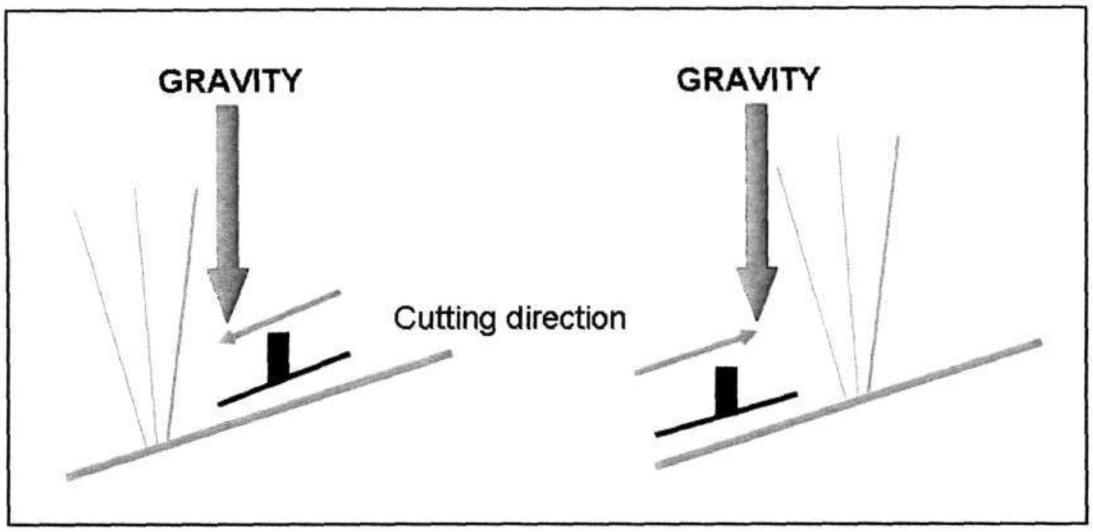

Figure 5.8 Extra energy required to swing the weight of the machine against the gradient of the slope and the force of gravity making it difficult to harvest on slopes >75% using System 2

Time and motion studies from 2005 showed a high downtime which was caused by changing blades, re-fueling and maintenance. A decision was made to purchase another two machines which were rotated during harvesting. The foreman insured that the machines were full of petrol, the blade was sharp and the filter did not require cleaning, hence the operators were only required to rotate the machines if it was damaged or required re-fueling. This decreased the downtime from 42% in 2005 to 29% in 2006.

A time and motion study done on System 1 compared to System 2 showed that System 2 saved time and fuel because of not walking back down the lines. In reality both systems would be used depending on the steepness of the slope and the length of the lines. A time and motion study done in 2006 represented normal operating conditions (Figure 5.9). This showed the largest cause of downtime was lunch and breakfast break which was acceptable but was double that of manual harvesting. (Meyer and Fenwick, 2003). This might be due to the task system used in the manual system that, if implemented into the Illovo harvesting system might decrease downtime. If the operators are working to task, there is a tendency to finish the task rather then have prolonged rest breaks. Another way to decrease the downtime was to ensure that there was an efficient foreman ensuring no time was wasted during re-fueling, maintenance, changing blades and air filters. This would result in a saving of 9% downtime. Resulting in efficiency greater then 70% and an increase in tons cut of between 3 and 5 tons per day.

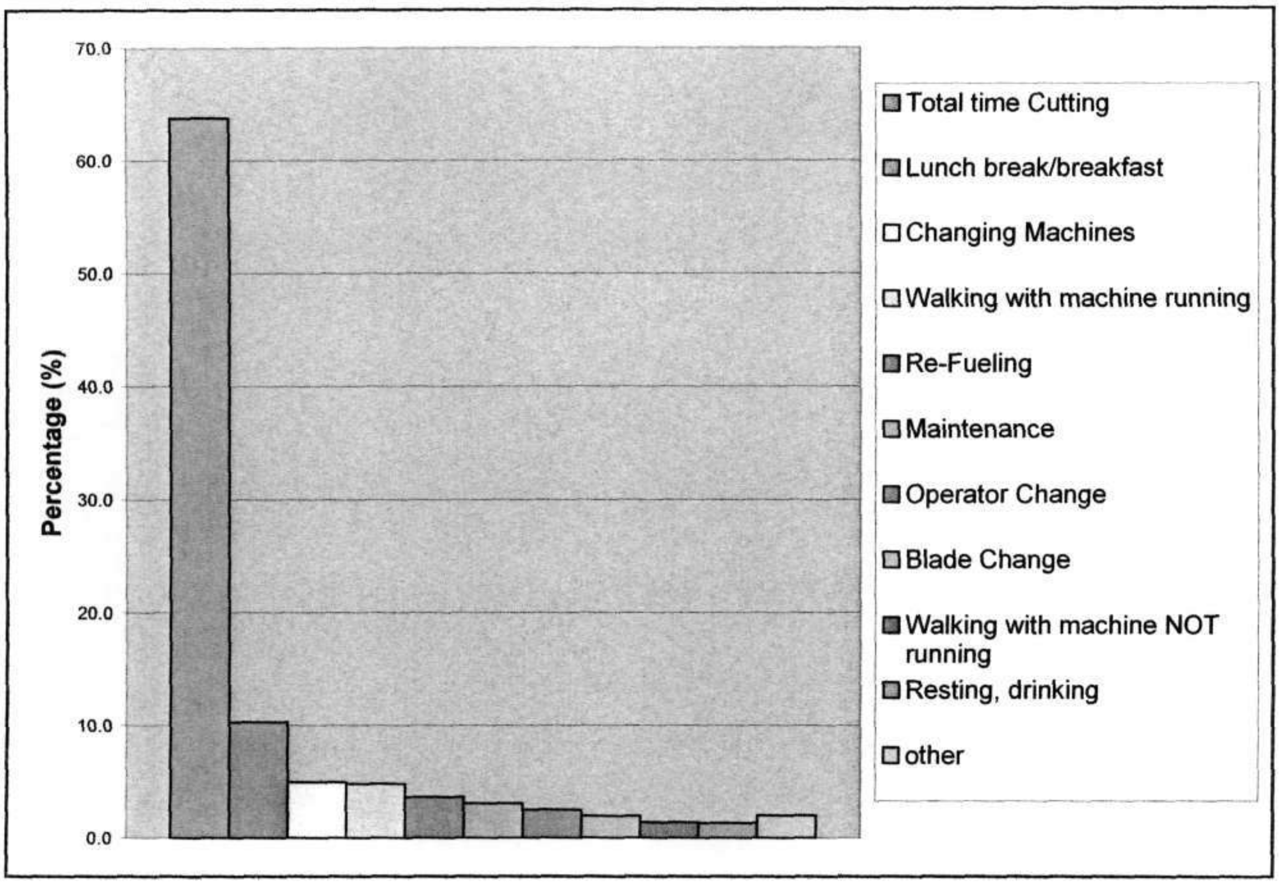

Figure 5.9 Time and motion study done in 2006 over three days

5.4.2 Performance

A summary of the 2005 and 2006 results can be seen in Table 5.1 and 5.2, respectively. Results show the different rates while the machine was operating and while the harvesting team was in-field. The difference depicts the amount of downtime. Detailed results can be seen in Appendix C.

Table 5.1 summarises the initial results in 2005 obtained after 29 days of harvesting. The average cutting rate was 1.4 $t.hr^{-1}$, but with an alarming 42 % downtime. The downtime was attributed to changing blades, re-fuelling and changing air filters. When the machine was operating, an average output of 2.5 $t.hr^{-1}$ (maximum 4.4 $t.hr^{-1}$) was maintained. The 2005 results were mainly obtained testing in fields with low yields (average 47 $t.ha^{-1}$). This also affected the output, since higher yields require less area to cover.

This identified downtime as a problem area and an effort was made to deduce this to realistic levels. The first step was to use three machines so that the cutter could continue with a functional machine if a machine had to be stopped. Other steps included different blades and a new filter system.

Table 5.1 Summary of results for 2005 cutting season for 29 days using System 1 and System 2

	Total tons	Machine operating		In- field		Downtime
	($t.day^{-1}$)	($t.hr^{-1}$)	($ha.hr^{-1}$)	($t.hr^{-1}$)	($ha.hr^{-1}$)	(%)
Average	8.15	2.50	0.05	1.44	0.03	42.25
Standard Deviation	3.01	0.78	0.02	0.59	0.01	13.35
Maximum/Best	13.30	4.43	0.09	3.47	0.07	18.89

The 2006 (Table 5.2) results show operation using Design D (Chapter 4.4). The average tons cut per day increased by approximately 5 tons and was attributed mainly to the decrease in downtime from 42 % to 29 %. The average yield harvested was 74 $t.ha^{-1}$ which was 57 % higher then the 2005 yields. This was expected to significantly increase the harvesting rate but, only increased the cutting rate by 18 %. It is interesting that the average tons cut per day almost equalled the maximum cut in one day in the 2005 season, showing a marked improvement.

Table 5.2 Summary of results for 2006 cutting season using both System 1 and System 2

	Total tons	Machine operating		In- field		Downtime
	($t.day^{-1}$)	($t.hr^{-1}$)	($ha.hr^{-1}$)	($t.hr^{-1}$)	($ha.hr^{-1}$)	(%)
Average	13.01	3.05	0.04	2.12	0.03	29.32
Standard Deviation	4.36	0.85	0.02	0.56	0.01	7.13
Maximum/best	19.60	4.59	0.07	3.20	0.05	14.88

A comparison was needed between the ISH and other current methods of harvesting, namely, manual harvesting. A direct comparison between manual cutting and the ISH can be seen in Figure 5.10. Figure 5.10 shows that cane was cut using the ISH at a $t.hr^{-1}$ rate of more then double that of manual harvesting but per day it was marginally more by an amount of 3 $tons.day^{-1}$. This was due to the high downtime of the Illovo harvester. The tons per man day to cut was lower then manual harvesting and was attributed to having two operators, hence the output had to be halved. The maximum tons cut in a day for the ISH was almost 20 tons (Table 5.2) and would be more competitive when compared to the tons per man per day.

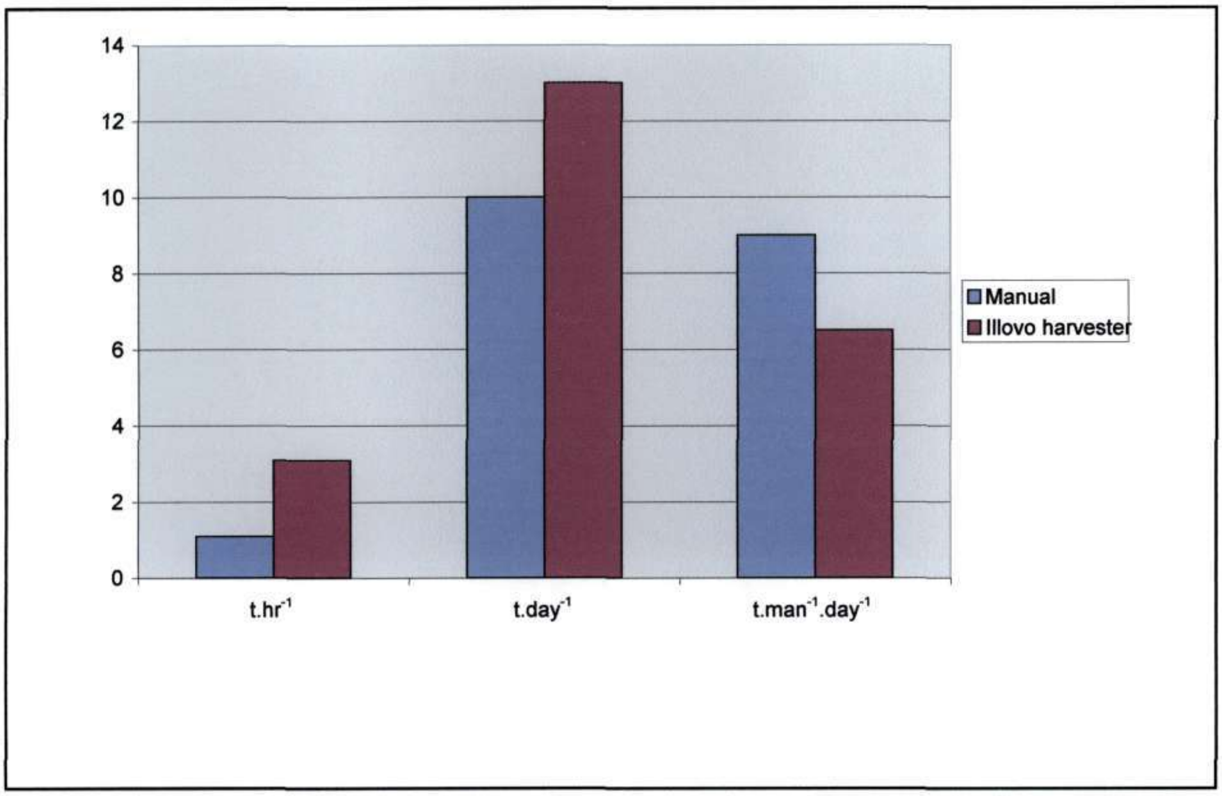

Figure 5.10 Comparison of cutting rates between the current manual harvesting system and the Illovo sugarcane harvesting system for the 2006 season

The machine did not work well in lodged cane and it lost productivity rapidly (1.8 $t.hr^{-1}$), (Figure 5.11). This was due to the machine getting caught and the operator not being able to complete the swinging motion. Another factor was that the puller was unable to pull the cane efficiently due to cane being lodged in other rows.

Operating in different cane varieties did not significantly affect the cutting rates. Stones decreased the harvesting rate because the blades had to be changed more often and the operator had to be more careful when cutting, he also had to wait for the puller to remove large stones. Lodged cane in fields with lots of stones caused high blade breakages and machine damages.

Figure 5.11 Operating in lodged cane decreased the cutting rate to approximately 1.8 $t.hr^{-1}$

5.4.3 System costs

Table 5.3 depicts the breakdown of the average, best and most likely costs for the 2006 season using the Illovo Sugar cost structures. The most likely costs take into account the higher wages expected to be paid to trained persons. It was within the costs for manual harvesting (± R14.00 per ton). It was assumed that a well managed production system could decrease the costs. The percentage breakdown for the average costs for 2006 can be seen in Figure 5.12 and the most likely breakdown in Figure 5.13. The cost percentages were similar with labour costs being the major contributor to the total cost.

Table 5.3 Summary of cost breakdown for the 2006 season

	Average	Best	Most Likely
Labour ($R.ton^{-1}$)	8.74	5.81	9.52
Blades ($R.ton^{-1}$)	2.23	0.95	1.46
Capital ($R.ton^{-1}$)	0.54	0.36	0.47
Fuel ($R.ton^{-1}$)	2.89	1.92	2.51
Maintenance ($R.ton^{-1}$)	1.44	0.96	0.75
Total ($R.ton^{-1}$)	15.84	9.99	14.72

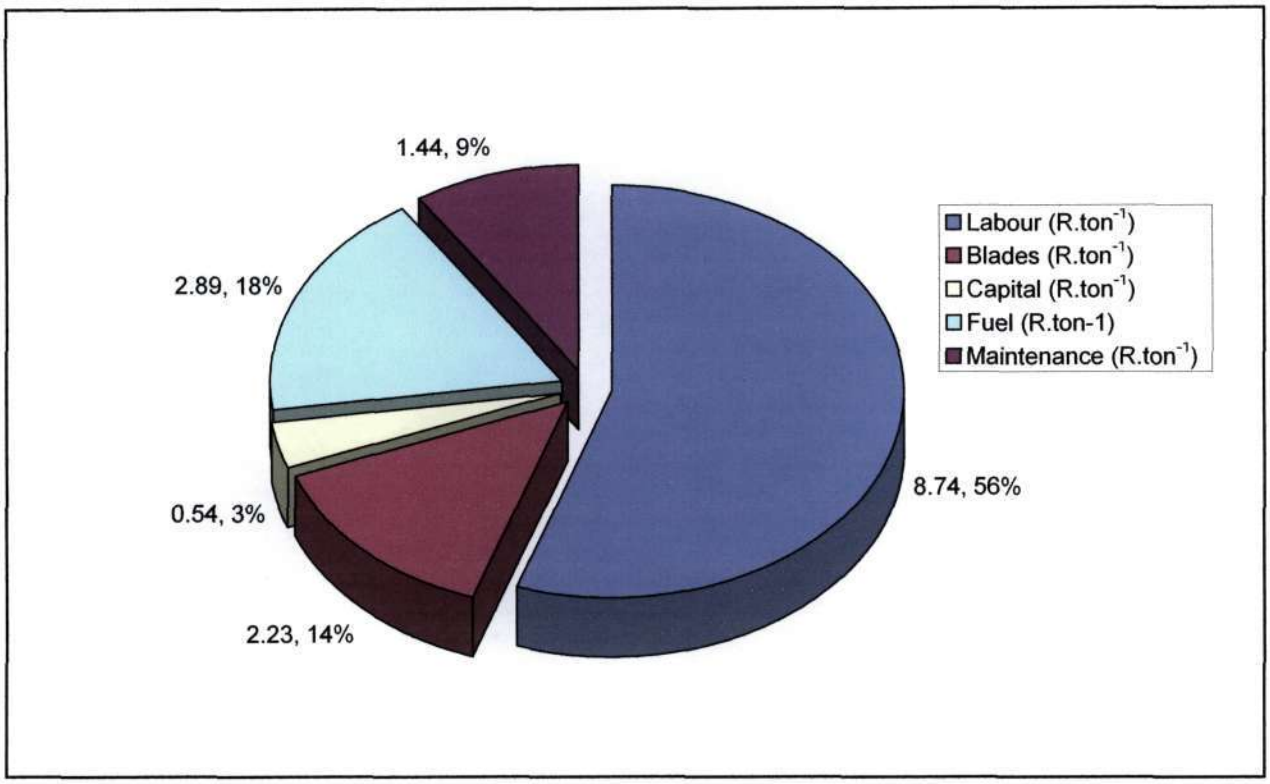

Figure 5.12 Average cost breakdown for the Illovo sugarcane harvester during 2006

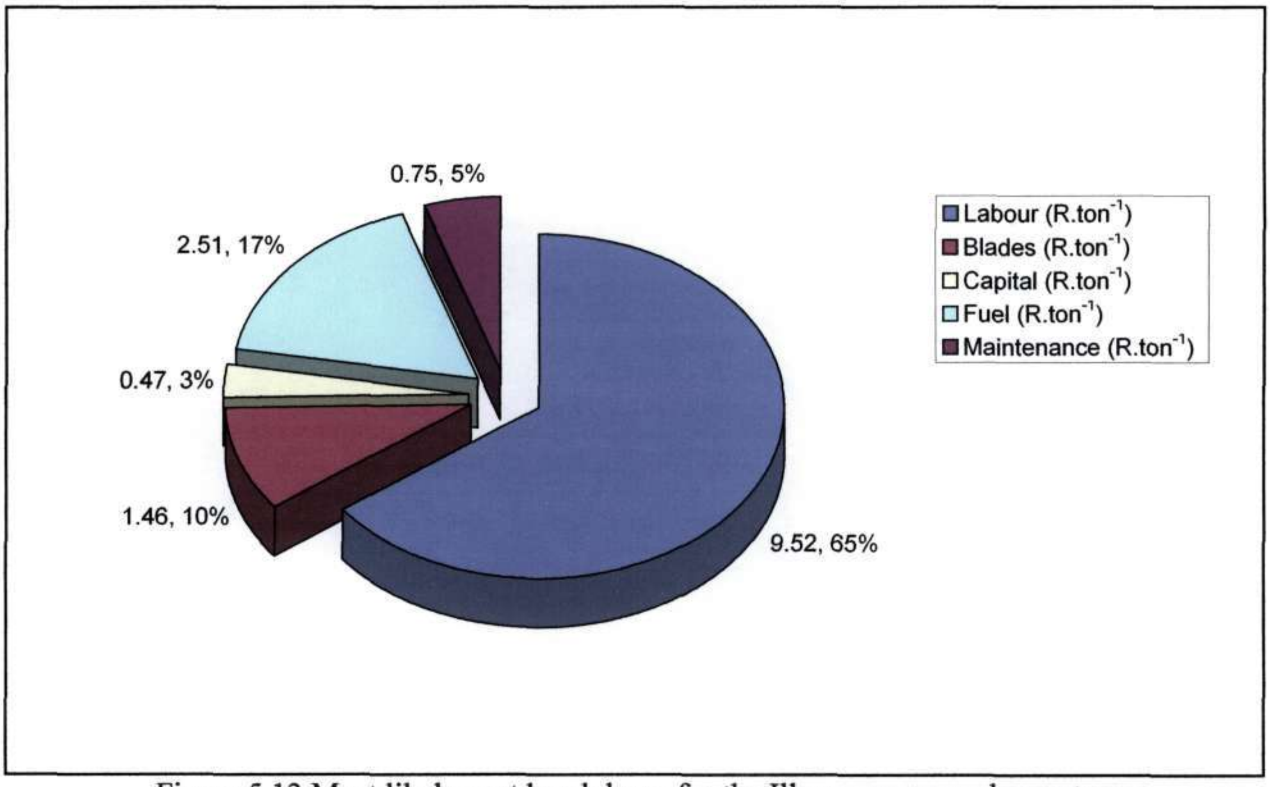

Figure 5.13 Most likely cost breakdown for the Illovo sugarcane harvester

5.4.4 Machine durability

In determining the costing of the system it was assumed that a single machine would last one harvesting season, if three were used in rotation they would have to last 3 years. The machine needed to be cleaned and serviced daily and the normal maintenance included:

1. Cleaning of the air and fuel filters,
2. cleaning the gear head,
3. check sparkplug and the engine rpm, and
4. general inspection on connection points and any wear and tear.

Due to the mass of the blade the engine tended to over rev. The carburettor settings were hence adjusted to account for this and the rpm was dropped from 12 000 rpm to 10 000 rpm. This did not affect the operation and saved fuel.

It was noted that the machine had a number of problems throughout the harvesting period. Many of these problems were alleviated due to the adaptations in Chapter 4.2.3. There was however still issues that required further investigation. A list can be seen in Table 5.4 with relative comments. Another popular brushcutter was tried but proved to not be as robust as the STIHL.

Table 5.4 Breakages that occurred during testing

Breakage	Number of times	Hours Worked	Solved	Comments
Sparkplug	regularly	na	Yes	Requires changing every 30 hrs working
Seized engine	1	71	Yes	New filter installed
Gearhead	5	na	Yes	Grub screw inserted stopping the gearhead pulling off
Snapped Shaft	3	na	No	Blades breaking cause vibrating.

The major breakages incurred were the seizing of the engines caused by inadequate filters and the bending of the shafts and consequent breaking of the vibrating unit. The bending of the shafts and breaking of the vibration unit were caused by rough or careless handling. It was more susceptible to happen in lodged sugarcane and rocky fields. The outcome is seen in Figure 5.14 and the major factor was an unbalanced blade that caused the machine to vibrate to such an extent that it shattered its mountings and bent the main drive shaft.

Figure 5.14 Machine that has broken the vibrating units, notice the broken blade depicted with the red arrow

The machine could not last a full season without some significant and expensive repairs. Most of the damage was attributed to the heavy blade and unrealistic working conditions. Further research and work is currently being done on the blade to decrease the mass by 500 g. This should reduce the downtime significantly. Another change that may help is inserting ribbing on the shaft to strengthen it. Recommendations for optimal cutter efficiencies require field conditions that have:

1. Flat culture (i.e. not planted in furrows or on ridges),
2. minimal stones,
3. erect cane, and
4. slopes less then 75%.

5.4.5 Safety

The total operating time on the ISH was approximately 500 hrs with no serious injury occurring. Christie (2006) compared harvesting sugarcane with the ISH to the timber chainsaw operation. The conclusion was that it was safer but still required safety measures and preventative steps were needed to ensure that no injuries took place. The safety measures were determined for each task (cutter, puller and sorter) and shown below.

CUTTER

The brushcutter has a guard (Figure 5.15) that protects the vital organs (chest, face and head) from the spinning blade and the operator has the least chance of any object being flung into his eyes. The throttle control bar, circled in blue in Figure 5.14, prevents the cutter from getting close to the blade and keeps it away from the cutters feet.

Figure 5.15 Protective gear worn by the cutter with the blade guard (circled in red) and throttle bar (circled in blue), preventing the operator from placing his body near the blade

The cutter was required to wear the following protective gear:

1. shin guards with long pants,
2. industrial, steel capped boots,
3. goggles or glasses,
4. ear muffs, and
5. a face mask for dust.

The cutter should be continually aware of the position of the blade. This was done by always facing forward in the direction of the blade. When walking with the machine it needs to be turned off or the cutter should walk ahead of all other team members.

PULLER

The puller was placed at a higher risk compared to the cutter. The puller must not move further forward than the throttle bars shown in Figure 5.15 and must assume that the cutter is not watching where the blade is. It is advised the puller never faces away from the blade or the cutter. It was the pullers responsibility to move rocks out of the way if need be. This should be done first with the staff, but if not possible then the puller must move forward once the cutter has decelerated and has placed the blade on the other side of the line of cane. It is also the pullers responsibility to look for potential problems, e.g. other persons.

The puller should wear the same protective gear as the cutter (Figure 5.15). Regular changing between pulling and cutting will keep the workers alert and will reduce the risk of injury.

SORTERS

The sorters are the safest and require no safety equipment. The sorters must ensure they do not work in front of the cutter or the puller, due to the risk of blades breaking and being flung forward. The sorters must keep up with the cutter and puller when removing the cut cane and putting into a single windrow. This was to ensure that the harvesting team have a clear path for cutting. Special care must be taken when using System 1 due to walking back and forth of the cutter. There was a higher likelihood of an injury happening with System 1, therefore where practical System 2 is recommended.

5.5 Conclusion

The Illovo sugar harvesting system uses two basic systems, System 1 and System 2. System 2 uses a block formation and was the more efficient system but cannot operate on steep slopes (> 75 %) therefore, System 1 is recommended in the steep areas.

Due to the development of the system and the reduction in downtime, the ISH had a marked improvement in the 2006 season. This was attributed to implementing two more machines that rotated during the work shift. The output during 2006 was 13 $t.day^{-1}$ with a machine output of 3.05 $t.hr^{-1}$. The best results achieved were 19.6 $t.day^{-1}$ with a machine output of 4.59 $t.hr^{-1}$. The downtime was still too high and it was assumed that by implementing a task system where the Illovo sugarcane harvesting team is tasked a set amount of tons to cut per day will increase the productivity.

The cost of operating was approximately R15.84.t^{-1} and was competitive compared to the conventional manual harvesting. This value per ton was expected to be reduced significantly when a full system is implemented with experienced workers. Estimated reduced values were approximately R14.72.t^{-1}. Labour costs contribute the greatest amount at 65 % followed by fuel (17 %), blades (10 %), maintenance (5 %) and capital outlay (3 %).

Safety is a concern, but by using adequate safety equipment and with good supervision this should not be a problem. The most dangerous operation was that of the puller and he should be kept alert by regular changing between cutting and pulling.

The system is an economically viable solution and with reduced labour availability for manual cutting, it would hopefully make the task of cutting cane more attractive and raise the status of sugarcane cutting. More work, however, needs to be done to decrease downtime, improve management, introduce change management and convince labourers and farmers about the advantages of the system. A detailed method of changing management and systems is outlined in Appendix E. This could be used to ensure a smooth transition from one harvesting system to another.

The system still required analysis from a human perspective. This entailed ergonomic studies that analysed the system and its impact on a person. This is outlined in the following Chapters.

6. ERGONOMIC PRINCIPLES IN HARVESTING SUGARCANE

Sugarcane is not easily harvested, manually or mechanically. Mature sugarcane may assume a variety of positions and shapes, from reasonably erect and straight, to heavily lodged and curved (Royce, 1996). From Chapter 2 it is evident that the most efficient harvesting method is by hand, which is strenuous and labour intensive (Meyer and Fenwick, 2003). Since a large portion of the sugarcane in South Africa is planted on steep slopes, manual harvesting is unlikely to change (Meyer and Fenwick, 2003). Thus, an understanding of the human body and the measurement of human responses is required so that harvesting can be made more productive while at the same time not over taxing the workers.

6.1 Background

Wilson (2000) defined ergonomics as the theoretical and fundamental understanding of human behaviour and performance. He also concluded that ergonomics is the study of work and systems that combine humans and machines. Ergonomics is intended to maximize productivity by reducing operator fatigue and discomfort and so improve the efficiency of the worker (Scott and Christie, 2004). Ergonomics tends to focus on changing aspects of the task rather than selecting workers who are more capable of doing the work. As there are very few task adjustments that can be made when harvesting sugarcane manually, it is necessary to obtain a better understanding of the physical workloads imposed on these workers. The goal of ergonomics is to recognise the mental capabilities and limitations of the worker as the worker interacts with the work environment (Rosskam, 1996).

There are many potential ergonomic problem areas of a worker, seen in Figure 6.1. Most of the problem areas, such as the cardiac circulatory system, metabolic system and strains to the skeletal and muscular system are obvious to an employer. However, issues that involve the psycho-social aspect are not as obvious and are often as important (Christie, 2002, Scott *et al.*, 2004).

Scott *et al.* (2004) commented that there was a need to create awareness among employers and employees about the basic principles, application and benefits of ergonomics. This was to give the responsibility to both the employer and the employee to recognise potential problem areas and to stop the work being performed or change the methods before it affected the worker.

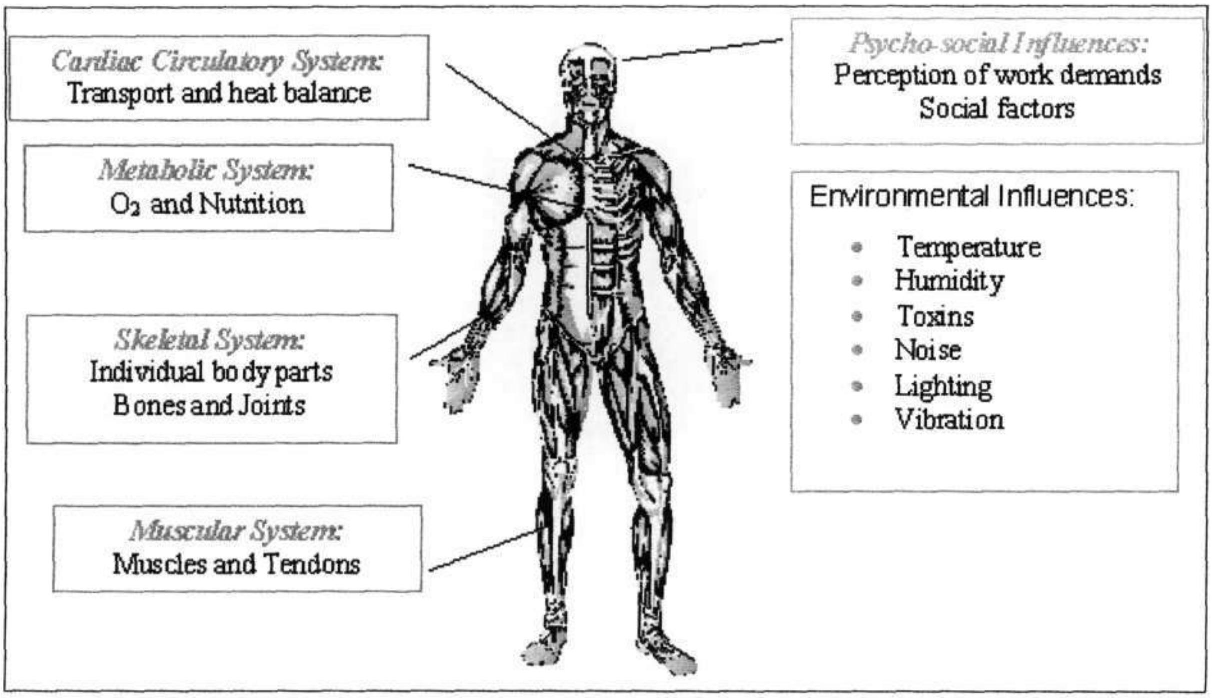

Figure 6.1 Potential ergonomic problem areas of a worker (Scott *et al.*, 2004)

6.2 Relevance of Ergonomics in a Developing Country

The importance of keeping tasks within the sustainable physical capabilities of the worker has been known for over a century and is easily adhered to in first world countries (Christie, 2002). In first world countries which have less poverty, set ergonomic limits are generally adhered to, whereas workers in developing countries simply accept sub-optimal working conditions as the 'norm' and in such conditions the energy expenditure of job requirements tends to be high (Christie, 2002). O'Neill (2000), however, questioned the relevance of ergonomics in a developing country like South Africa.

According to O'Neill (2000), a common approach in developing countries is to rather pay a small salary, but to a larger number of people, so as to keep the levels of unemployment down. This, however, has a detrimental effect on the workers making them unproductive as illustrated in Figure 6.2. This cycle of poverty can only be broken by strong interventions at the arrows in

Figure 6.2. There would seem to be scope for ergonomics to increase the 'Low working capacity' to 'Moderate working capacity'. This could be done by increasing the training and supplying better working equipment that will in turn increase the productivity. This would result in slightly higher incomes and hence better health. As a consequence, the workers capability and productivity will improve and be optimised.

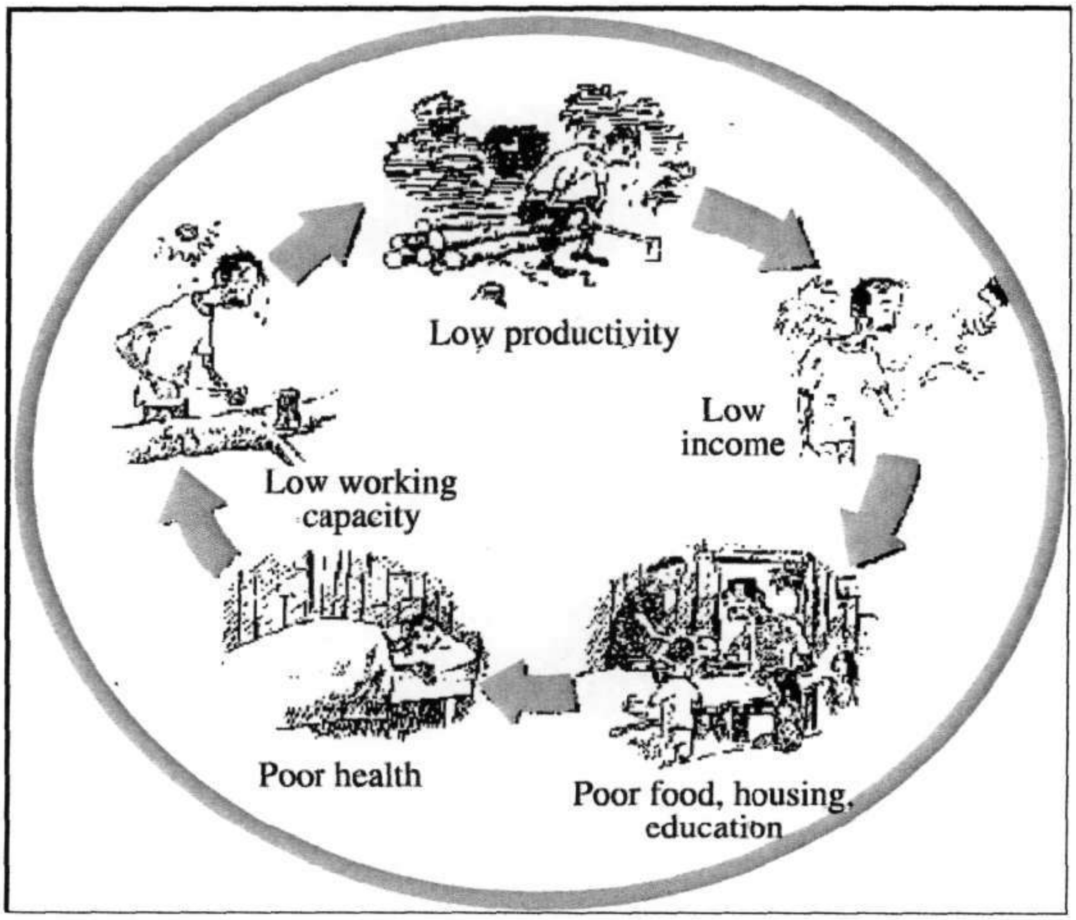

Figure 6.2 The circle of misery of workers in developing countries (O'Neill, 2000)

O'Neill (2000) concluded that it may be difficult to apply ergonomics in a third world country, but it is still vital to attempt to maintain the productivity and not be detrimental to the worker. The goals and principles of a productive society do not change, but the route taken to achieve this may be different between a first and third world country.

6.3 Measuring Energy Expenditure

There are two methods for accurately determining energy expenditure, namely, direct calorimetry and indirect calorimetry (McArdle *et al.,* 2001). Direct calorimetry measures the body's heat production which is correlated to the energy consumed, while indirect calorimetry measures the oxygen consumption that is directly related to energy expenditure (McArdle *et al.,* 2001). Calculation of energy expenditure using these techniques is relatively easy and simple under laboratory conditions, but is more complex when trying to evaluate in-field conditions (Scott and Christie, 2004). As a generalisation therefore, many field studies do not directly assess oxygen uptake with expensive ergospirometers, but rather predict oxygen uptake by establishing individual heart rate/oxygen uptake calibration curves during an exercise test and not while working. Working heart rates are then used to predict oxygen uptake from the regression analyses.

6.3.1 Estimating energy expenditure from oxygen uptake

It is possible to determine the volume of the oxygen consumed (VO_2) using a portable ergospirometer which is an indirect method of calorimetry (McArdle *et al.,* 2001). The subject inhales ambient air with the constant composition of 20.93% oxygen, 0.03% carbon dioxide, and 79.04% nitrogen. The changes in oxygen and carbon dioxide concentration expelled during physical exertion compared with the percentages of these gases in ambient air (air taken in) shows the amount of oxygen consumed and hence the energy expended (Lothian and Farrally, 1995). This however, needs to be calibrated correctly to ensure accuracy of results.

Equations 6.1 and 6.2 are adapted from McArdle *et al.* (2001). To obtain the energy expenditure (EE) in kJ per min, the volume of oxygen ($L.min^{-1}$) consumed is multiplied by the constant 20.1 as shown in Equation 6.1. Measured VO_2 can either be absolute ($L.min^{-1}$) or relative to body mass ($mlO_2.kg^{-1}.min^{-1}$). EE is related to the body mass and if VO_2 is measured in litres per minute it is required to be multiplied by the body mass. This is then multiplied out by the total time doing the task to obtain the total energy expenditure. To convert EE from kJ to kilo-calories, where a calorie is defined as the amount of energy (heat) needed to raise the temperature of 1 gram of water by 1°C, EE is divided by the constant of 4.186.

$$EE = \dot{V}O_2 \times 20.1 \qquad (6.1)$$

where:

EE = Energy expenditure ($kJ.min^{-1}$)

VO_2 = Volume of oxygen ($L.min^{-1}$ or $ml.O_2.kg^{-1}.min^{-1}$)

6.3.2 Relationship between VO_2 and heart rate

Astrand and Rodahl (1986) found a linear relationship between heart rate and oxygen uptake. Therefore, by measuring the heart rate it is possible to predict the oxygen uptake and hence the energy expenditure of a person. It is noted that the regression analysis becomes unreliable at lower heart rates and care must be taken when evaluating heart rates below 120 bpm (Astrand and Rodahl, 1986). Nielsen and Meyer (1987) concluded that the relationship between heart rate and oxygen uptake differs from subject to subject due to sex, age and physical fitness. It is thus necessary to get individual relations for each subject (Maas *et al.*, 1989). McArdle *et al.* (2001) and Livingstone *et al.* (1999) outlined some other limitations caused by factors that affect the heart rate which might skew the results. These include ambient temperature, food intake, emotional stress, body posture, muscle groups exercised and pregnancy. Knowing the limitations, this method still allows for an easy, unobtrusive method that does not hinder the subject in performing the necessary tasks (Livingstone *et al.*, 1999, Bot and Hollander, 2000).

6.4 Perceived Exertion

Measuring only the energy expenditure does not give a true reflection of the demands of the task (Borg, 1970). A method used to assess how hard workers perceive they are working, is by measuring perceived exertion. Borg (1982) suggested that perceived exertion is the single best indicator of the degree of physical strain. This is because it integrates all of the body's responses and problem areas (as shown in Figure 6.1). Measurement of energy expenditure do not take into account the demands placed on the musculoskeletal system, therefore energy expenditure on its own is not a fair reflection of the total exertion (Straker *et al.*, 1997).

Borg (1970) developed a rating system that by, questioning the subject, it is possible to obtain an indication on how the worker is feeling with respect to the demands of the job. This scale (Table 6.1) was developed to increase linearly with exercise intensity for work on a cycle ergometer since oxygen consumption and heart rate increases linearly with work load.

Table 6.1 Rating of perceived exertion (RPE scale, after Borg, 1970)

Value	Verbal
6	
7	very, very light
8	
9	very light
10	
11	fairly light
12	
13	somewhat hard
14	
15	hard
16	
17	very hard
18	
19	very, very hard
20	

The scale ranges from 6 to 20 and denotes heart rates ranging from 60 to 200 bpm. This relationship, however, is not intended to be taken too literally since the RPE scale does not take into account age, type of exercise, anxiety and stress among other factors (Borg, 1982). There are some limitations that include communication and a lack of understanding by the worker (Scott *et al.* 2004). Hence, care must be taken and where needed, a translator must be used. Straker *et al.* (1997) also noted that subjects tended to over-estimate low workloads and under-estimate high workloads, but this is probably due to perceptions.

6.5 Occupational Low Back Disorder (LBD) in the Work Place

Lower back disorders (LBDs) continue to be the most common musculoskeletal problem in the work place and are one of the leading causes for absenteeism (McGill, 1997, Jorgensen *et al.*, 1999, Marras *et al.*, 1999 and Marras, 2000). It accounts for one-forth of all work related injuries and one-third of all compensation costs in the U.S.A. (McArdle *et al.*, 2001). There is thus a need to evaluate the lower back with the aim to predict whether there may be an injury when performing specific tasks (Ferguson and Marras, 2004).

A problem with determining work and back movement limits is that most LBDs occur due to repetitive movements and not a single event. Figure 6.3 shows how the back tolerance decreases over time due to damage of tissue (McGill, 1997). The red arrow shows where failure occurs even though the subject has not increased the applied load. Another factor that makes it difficult to determine limits is that every person is different and has different tolerance levels due to physique and strength (McGill, 1997).

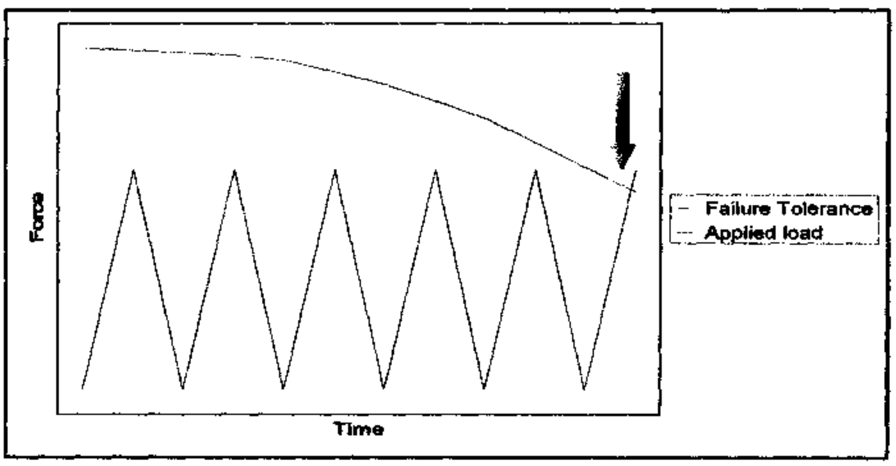

Figure 6.3 Repeated sub-failure loads lead to tissue fatigue and over time failure (after, McGill, 1997)

Many models and risk assessment tools for low back pain have been developed such as the NIOSH, 3-D SSPP, Psychophysics, LMM and TLV (McGill, 1997, Granata and Marras, 1999, Marras *et al.*, 1999, Marras, 2005). One of the most widely used risk assessment tools is the NIOSH model (Marras *et al.*, 1999). This categorisation classifies risk as:

- low risk = 0 incidences/200 000hrs,
- medium risk = between 0 and 12 incidences/200 000hrs, and
- high risk = ≥ 12 incidences/200 000hrs.

All these tools have several benefits that include, identifying high risk jobs, developing solutions to unknown problem areas, evaluating of specific solutions and identifying which specific features of a job are contributing to the elevated risk (Marras *et al.*, 1999). Marras *et al.* (1993) noted that most of these ergonomic techniques for controlling the risk of occupationally related LBDs use static assessment. This is problematic since many biomechanical models and epidermiologic studies show that the dynamic nature has a significant influence on the risk of occupational LBDs (Marras *et al.*, 1993, Granata and Marras, 1999). Marras *et al.* (1993) and Marras *et al.* (1995) developed a model of LBD risk based on actual workplace and trunk kinematic factors using the Lumber Motion Monitor (LMM). This model and type of results are the most likely to reflect the true nature of manual work (Allread *et al.*, 2000).

6.5.1 Lumber Motion Monitor (LMM) risk model

Marras *et al.* (1993) and Marras *et al.* (1995) calibrated the LMM risk model against 400 repetitive industrial lifting jobs. Existing medical and injury records were analysed for these jobs in order to categorise jobs into low-risk, medium-risk or high-risk.

The LMM is attached (Figure 6.4) and follows the lower back and represents an external spine that emulates and responds to the subjects' actual spine. It records the three dimensional movement, including the position, velocity and acceleration of the trunk (Allread *et al.*, 2000). The movement stresses and strains are transmitted to a portable computer wirelessly via an analogue-to-digital conversion board (Jorgensen *et al.*, 1999). A multiple logistics regression was then done between the existing data and the movement of the spine. It indicated five workplace and trunk motion features that can be used to classify jobs into different risk categories (Marras *et al.*, 1993, Marras *et al.*, 1995, Jorgensen *et al.*, 1999, Marras, 2005). These five workplace and trunk motions, as determined by Marras *et al.* (1993) are:

(i) lifting frequency,

(ii) load moment,
(iii) trunk lateral velocities,
(iv) trunk twisting velocities, and
(v) the trunk sagittal angle.

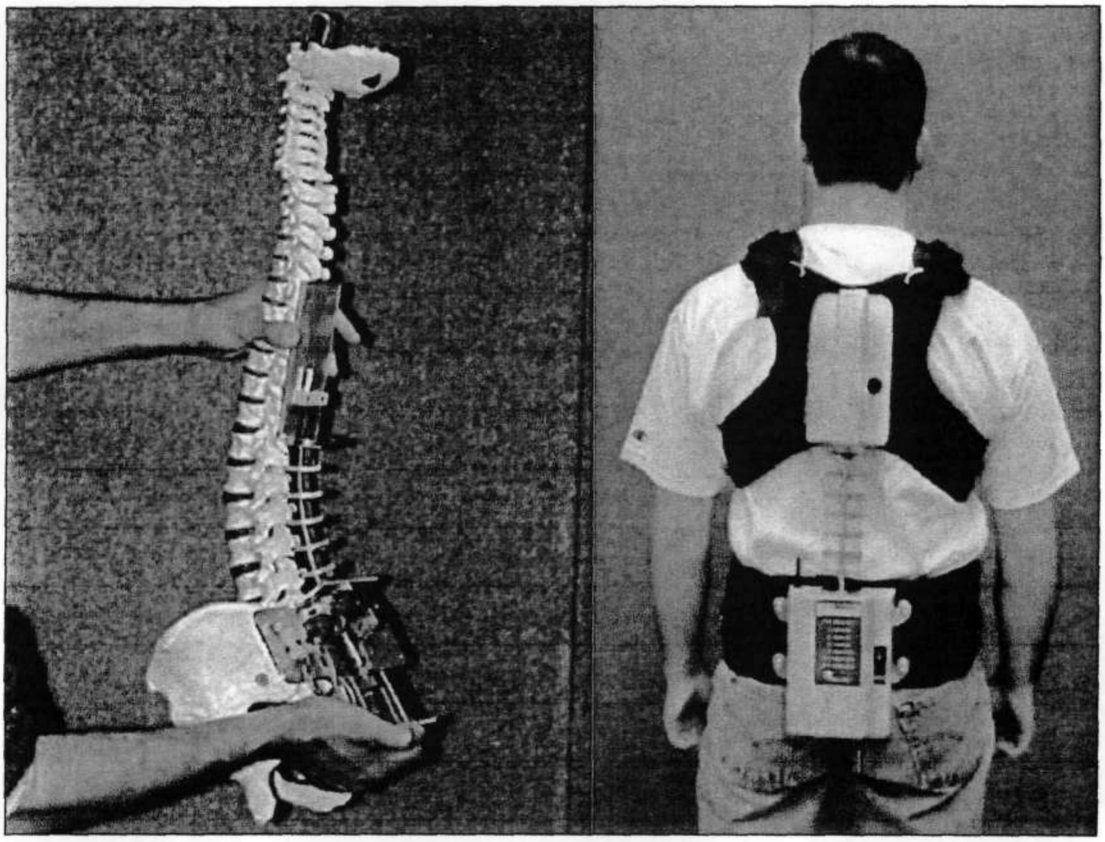

Figure 6.4 The lumber motion monitor and how it follows the spine (Marras, 2005)

6.5.2 Analysis of the LMM risk model

The model estimates the probability of a certain action being categorised in a high risk category (Marras, 2005). Figure 6.5 shows the five workplace and trunk movements with the different rates that correspond to the probability of being in a high-risk group. It is seen that any job or action that falls above the 60% probability can be classed as a high-risk and will more than likely cause injury over time (Marras, 2005).

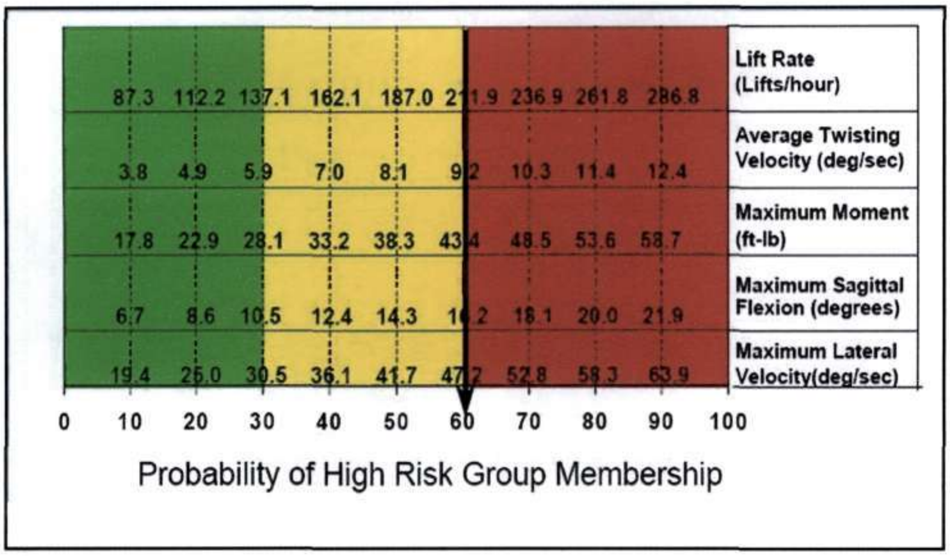

Figure 6.5 Five workplace and trunk movements correlated to the probability of being in a high risk group (Marras, 2005)

6.6 Ergonomic Studies on Sugarcane Cutters

According to Alba and Escober (1974), sugarcane cutting needs to be made more attractive and less strenuous by applying ergonomic principles. Various, but limited studies, have been done that show why sugarcane cutting is considered to be 'hard work' and how minor changes to the system can result in a large increase in productivity (Lambert *et al.*, 1994).

Lambert *et al.* (1994) conducted a survey on a sugarcane farm on the KwaZulu-Natal south coast. The aim was to determine the loss of body mass and energy expenditure between sugarcane cutters and stackers. The study analysed the split cut and stack system and showed where more energy was used.

6.6.1 Body mass loss and fluid intake

During an average day, the cutters and stackers studied by Lambert *et al.* (1994) both lost, on average, 2% of their body mass. Body masses all returned to their starting point within 24 hrs. Lambert *et al.* (1994) showed that there is a significant relationship between body mass loss and duration of the working day. Figure 6.6 shows a comparison between fluid intake to weight loss and indicates no significant difference in weight loss between stackers and cutters. The fluid intake consisted mainly of diluted, fermented maize meal porridge (referred to as *Maghewu*) which contains approximately 94% water. The error band for the amount of *Maghewu* consumed for cutters was 4.7 litres ± 0.1 and for stackers it was 4.8 ± 0.3. The energy intake related to 5179 ± 161 kJ for the cutters and 5281 ± 324 kJ for the stackers.

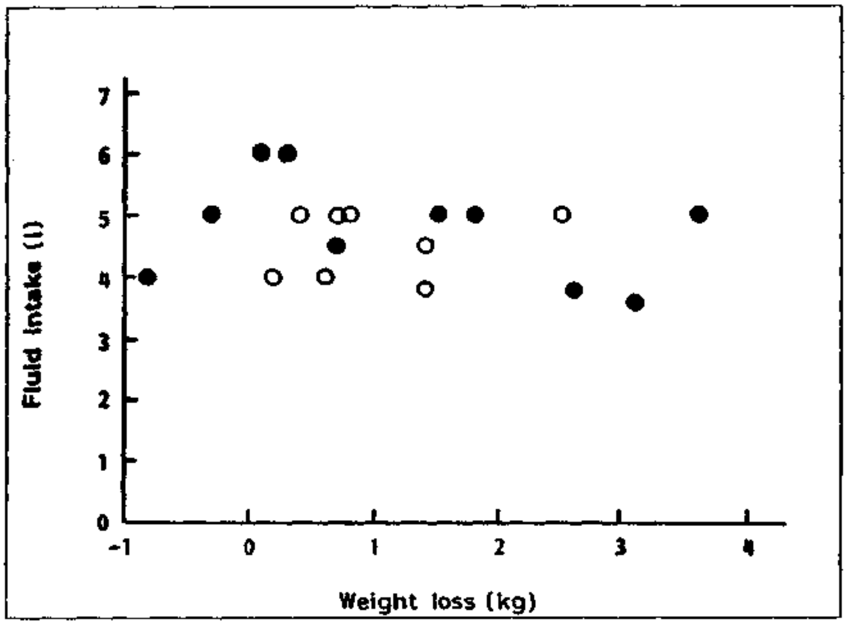

Figure 6.6 Fluid intake (litres) and weight loss (kg) for (○) cutters and (●) stackers (Lambert *et al.*, 1994)

6.6.2 Heart rate and energy expenditure

The average hourly heart rates for the cutters and stackers can be seen in Figure 6.7. Lambert *et al.* (1994) determined that the error band for the cutters heart rates for the entire day was 103 ± 3 bpm. This was significantly less than that of the stackers, which was 114 ± 4 $bt.min^{-1}$. Cutters, however, had a higher peak heart rate of 146 ± 6 $bt.min^{-1}$ compared to stackers of 138±5 $bt.min^{-1}$. According to Scott *et al.* (2004), no worker would be able to sustain this effort for long periods under the sub-optimal conditions associated with most harvesting tasks. Scott *et al.* (2004) suggests that heart rate responses to work load should not exceed 110 $bt.min^{-1}$.

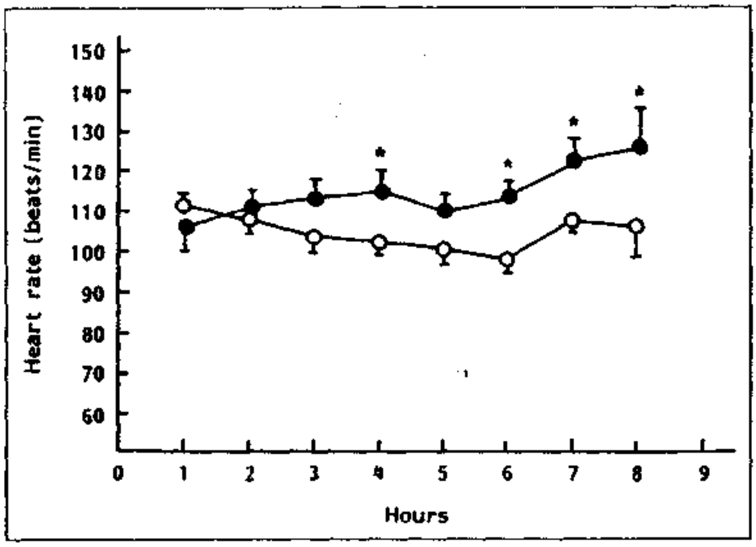

Figure 6.7 Average hourly heart rate for (○) cutters (n=11) and (●) stackers for an average working day (Lambert *et al.*, 1994)

These results confirm the results obtained by Smit *et al.* (2001) who found that the average maximal heart rates during cutting burnt sugarcane and green sugarcane were 131.13 and 135.87 $bt.min^{-1}$, respectively. The averages were found to be 119.8 ± 18.61 $bt.min^{-1}$ for burnt sugarcane and 123.67 ± 13.23 $bt.min^{-1}$ for green sugarcane. Smit *et al.* (2001) also concluded that the energy expenditure required for cutting burnt sugarcane was 10% lower than that required when cutting green sugarcane. Table 6.2 contains the results of energy expenditure and energy intake for sugarcane cutters and sugarcane stackers. Lambert *et al.* (1994) concluded that sugarcane cutters' and stackers' work can be classified as heavy work.

Table 6.2 Calculations of average energy intake and energy expenditure of cutters and stackers during one working day (after, Lambert *et al.*, 1994)

Variable	Cutters n=11	Stackers n=9
Energy Intake (kJ)	5179±161	5281±324
Energy Expenditure (kJ)	11695±1288	14127±1710
Rate of Energy Expenditure ($kJ.hr^{-1}$)	1577±130	1802±164
Energy Expenditure per tonne of sugarcane ($kJ.ton^{-1}$)	1325±119	1544±131

From the results in Table 6.2 it is evident that stacking uses slightly more energy and this is due to the stackers having to bend down, lift and carry 30-40 kg bundles up to 60 m and sometimes up inclines as steep as 40% (Lambert *et al.*, 1994). However, what is of major concern was the unacceptable imbalance between the nutritional intake of the workers and the energy expenditure required to do the specific tasks. This lack of nutritional resources affects the workers' physical and mental ability to effectively cope with the task. Mental sharpness and physical strength also deteriorate throughout the workshift, with little hope of adequate replenishment of food and rest when they go home after their workshift (Scott *et al.*, 2004).

6.7 Improving Sugarcane Cutters Productivity

Alba and Escober (1974) and Orane (1970) determined the following sugarcane cutter methods that, if applied, could increase the overall productivity:

- the grasping and cutting of three or more stalks at a time,
- when topping, making sure that the tops do not fall into the cut sugarcane or bundles,
- keeping the distance from the windrow to the uncut sugarcane as small as possible,
- throwing the cut sugarcane into the windrow without turning to look at the row,
- working at the coolest times of the day, i.e. from 8h00 to 12h00 and then again from 16h30 to 18h00,
- enforced frequent rest stops of 10 min every 1.5 hr. The optimum is 6 min every 1 hr but is unlikely to be easily implemented, and
- provision of good safety equipment, like gloves and goggles that are best suited to sugarcane cutting.

Some ergonomic factors that were reported by Scott *et al.* (2004) to increase productivity in timber harvesting include the following:

- the need for greater responsibility and involvement from all parties involved,
- to stop using the task system as this encourages an increase in the intensity of work and a reluctance to take a break,
- to supply nutritional supplements prior to going into the field, with fresh cool water available every hour throughout the work shift and tea or lunch with solid food supplement,

- to give basic educational explanations on why certain requirements are needed by the employer e.g. base cutting height, and
- the requirement for regular, good supervision.

As outlined by Rosskam (1996), wherever possible, mechanical power should be used to do tasks of heavy work. However, if this was not feasible, heavy work must always be varied throughout the day with lighter work and/or with rest periods at regular intervals. Stooping and picking up of heavy loads off the floor should be minimised. Other ergonomic factors include: reducing the mass of the sugarcane bundles and making it easier to handle, while also minimising the carrying distance and reducing twisting of the body.

Sugarcane harvesting is physically demanding and anything that makes the job more pleasant and easier will increase productivity. The employer needs to ensure that the cutter is correctly paid for the sugarcane that is harvested. If the system involves working in teams, it is not advisable to weigh the total cut sugarcane and divide by the number of cutters in a team. It is better to divide the tasks equally so that the each sugarcane cutter gets paid individually for the work performed. There is a reluctance to cut if the task is perceived to be too large to complete in the allocated time (Alba and Escober, 1974).

6.8 Conclusion

Ergonomics is a useful tool when used correctly to evaluate the work place and can significantly improve the productivity and prevent serious injuries. Manual sugarcane harvesting is defined as 'hard work' and further ergonomic studies and interventions are needed to lessen the demands being placed on the worker. This can help the worker make the job easier by reducing the energy deficit and decreasing the spinal compression and spinal forces. This in turn might increase the available work force that is steadily decreasing due to the HIV/Aids pandemic. New sugarcane harvesting systems need to be ergonomically verified to ensure that they are a feasible option before a forced change is implemented.

7. ERGONOMIC STUDY

An ergonomic assessment was performed to compare the physical demands being placed on manual sugarcane harvesters compared to workers who operated the ISH using the system described in Chapter 5. The manual system used was the cut and bundle method as described in Section 2.2 where an output of 4 tons per day was tasked to the worker.

7.1 Aims

There were three aims for the ergonomic study, namely:

1. Determine the energy expenditure using working heart rates and then heart rate/oxygen uptake calibration curves for the three tasks of the manual harvesting (cutting, topping and stacking) and comparing the energy expended for manual cutting against the energy expended when using the ISH.
2. Determine the perceived exertion using Borg's (1972) rating scale and assess where the workers felt discomfort as a direct consequence of the work tasks, using the body contribution map and rating scale.
3. Determine the risk category, using the LMM (Chapter 6.5), for the lower back for cutting comparing the manual and Illovo harvesting system.

These were considered separately and then evaluated that combined all of the factors to determine the method that was best from a human perspective.

7.2 Methodology

The study was conducted on the 6th and 7th of June 2006 on the Illovo Esperanza Farm on the South Coast approximately 60km south of Durban. A team from the Ergonomics Unit, Rhodes University, Grahamstown led by Dr. Candice Christie, who conducted the study using the available recognized methods. A group of 8 cutters (M2 – M9) were selected ranging from weak cutters to strong cutters so that there was a fair representation of the current cutting force. Two

ISH operators were also tested using the manual method as well as the newer method (M1 and M10). The analyses were split into three for the different aims shown above.

7.2.1 Energy expenditure

The energy expenditure was determined using the method outlined in Chapter 6.3. Every subject was weighed prior to working and their body dimensions recorded. A polar accurex plus or a polar sports tester heart rate monitor (Polar Electro, Kempele, Finland) was fitted to the subject prior to going into the field for a normal day's work. The heart rate monitor comprised of a wrist watch that received the heart rate information via an electrode strap positioned around the workers chest below the inferior border of the pectoralis major. The watch worn on the wrist served as a display unit and stored the heart rate data. For the Illovo sugarcane harvesters, the watch was strapped to their back since the frequency of the brushcutter interfered with the transmission, hence, the watch was required to be close to the electrode strap. Following work, the heart rate monitors were removed and the heart rates were downloaded for the duration of the work shift onto a PC via the Polar Interface Plus SystemTM (Polar Electro, Kempele, Finland) for Windows TM (Microsoft Corporation) and the data then exported into ExcelTM (Micosoft Corporation).

Throughout the workshift the activity performed was noted and then correlated to the heart rate at that specific time. This was used to determine the energy expended for the different activities e.g. cutting, topping and stacking. The heart rates range was required when performing the step up test to determine the calibration curves for the predicted VO_2.

Once the subject had completed the task for the day, they were required to go directly to the make-shift laboratory in an open area alongside the work area. The worker was required to sit quietly for 30 min, before participating in a progressive step test within the same ambience as experienced during the work shift using a portable ergospirometer to determine the volume of VO_2 consumed.

The worker was fitted with an ergospirometer ensuring that the correctly sized face mask was used. The ergospirometer used was the K4b^2 (Cosmed®Rome) which was calibrated prior to each session. This was done using a Hans Rudolph 3 L syringe for the volumetric calibration. The gas analysers were calibrated initially against ambient air and secondly using a 16.10 % O_2, 4.90 % CO_2 and 79 % N_2 mixture. The worker was fitted with the unit (Figure 7.1) containing oxygen and carbon dioxide analysers, as well as a sampling pump, UHF transmitter, barometric sensors and electronics that were powered by a battery. The battery was a 0.8 kg portable unit that was fixed to the subjects back by means of a harness as seen in Figure 7.1. A receiver unit collected and stored the data that was transmitted by telemetry from the portable unit. The heart rate and VO_2 data were recorded simultaneously throughout the progressive step test and the data was downloaded and exported to ExcelTM (Microsoft Corporation).

Figure 7.1 The portable K4b^2 (Cosmed®Rome) ergospirometer used to determine the HR/VO_2 relationship

The key principle of the step test was that similar ranges of heart rates experienced during the work shift were reached during the step test. Therefore, each subject was able to be calibrated for their own VO_2 consumption against their heart rate. The height of the bench for the step test was 350 mm. Each workload was retained for 3 min during which a steady state could be reached. The step increments were 82, 98, 114 and 139 steps per minute that was controlled using a metronome. This caused the subject to attain heart rates similar to that experienced in the work shift. Figure 7.2 shows a step test being performed using a metronome to maintain a steady state.

Figure 7.2 Step test using a 350 mm high step maintaining a steady state with the help of a metronome

Once the simultaneous data of VO_2 and heart rates were exported to ExcelTM (Microsoft Corporation) a linear relationship was determined. Using this linear equation it was possible to obtain a predicted volume of oxygen consumed (pVO_2) which could be correlated to the heart rates obtained during the work shift. The subjects were weighed and pVO_2 was determined in litres first, in order to calculate energy expenditure, and then predicted oxygen consumption was calculated relative to body mass in millilitres per kilogram of oxygen consumed per minute ($mlO_2.kg^{-1}.min^{-1}$). Using Equation 6.1 the EE was determined and multiplied by the time spent doing various tasks.

7.2.2 Perceived exertion and body discomfort

The perceived exertion was assessed using Borg's (1972) RPE scale as seen in Table 6.1, pg 79. Due to language barriers a Zulu-translated RPE scale, as seen in Figure 7.3, was used in conjunction with a translator. These perceptions were recorded at regular intervals throughout the work shift. Body discomfort was also measured using the body discomfort scale seen in Figure 7.3. The scale was divided into an anterior and posterior view of the human body. The subjects were asked to rate areas that are experiencing discomfort and then they were required to rate the intensity of that discomfort on a scale of 1 to 10 where 1 was minimal discomfort and 10 was extreme discomfort.

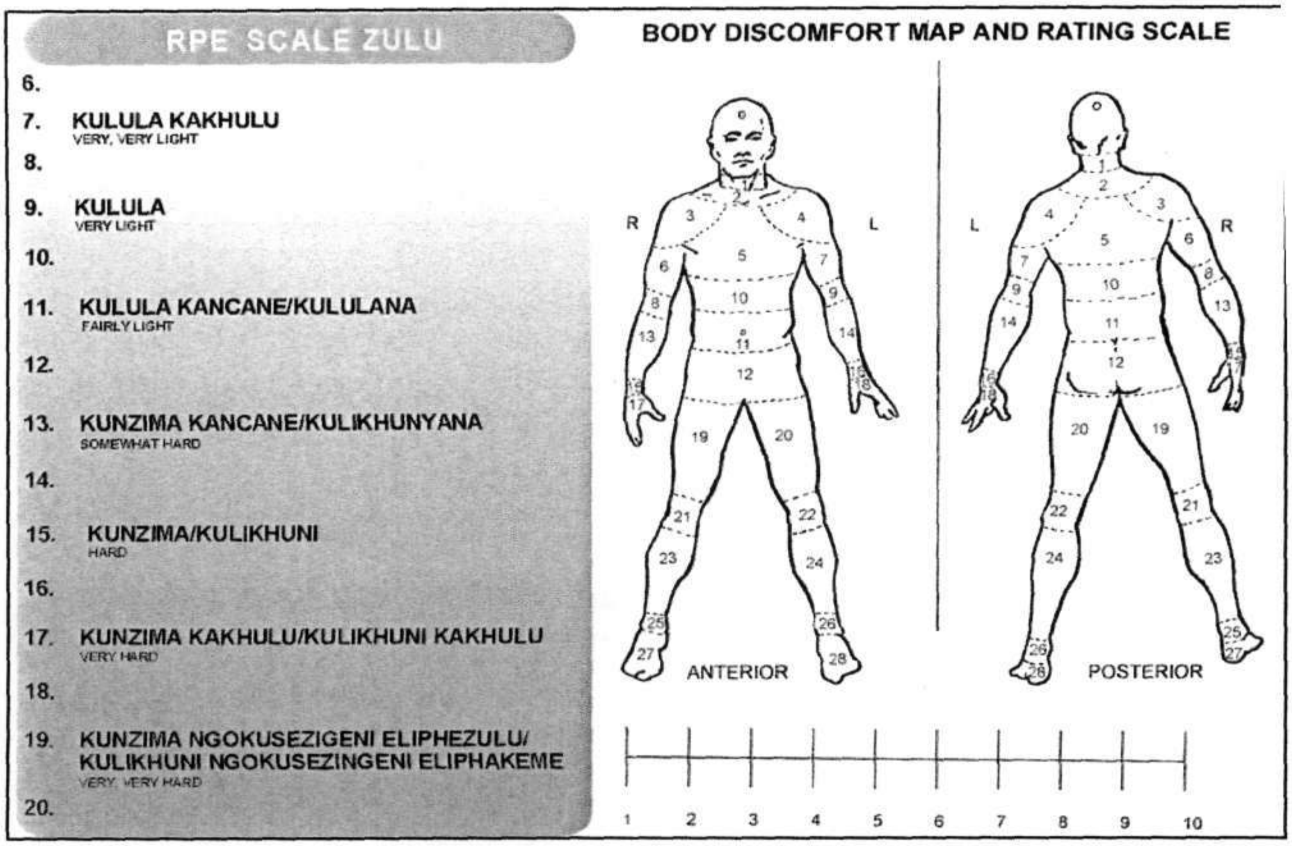

Figure 7.3 Zulu-translated RPE scale to determine the perceived exertion and a body discomfort map to determine pain experienced during the work shift (Scott *et al.*, 2004)

7.2.3 LMM risk model

The LMM was attached to the subjects (Figure 7.4) and measurements were taken for approximately 20 sec intervals for each work task, including cutting, topping and stacking for the manual method and cutting and pulling for the Illovo harvesting method. The data was transmitted to a PC using telemetry to allow for freedom of movement. The data was then exported to ExcelTM (Microsoft Corporation). In order to be able to make a comparison, the manual cutting action was compared to the Illovo harvesting method. This was due to the topping and stacking having to be done by both harvesting systems. For the cutting, a comparison was made with the three dominant motions (lateral, sagittal and twisting motion) of the lower back, which measured the position, velocity and acceleration of the subject's thoraco-lumber region in all three planes of the body.

Figure 7.4 The LMM being fitted to a subject ensuring freedom of movement

7.3 Results and Discussion

The results for cutting were more favorable for the ISH. The values for manual harvesting (cutting) were similar to the studies done by Lambert *et al.* (1994) and Smit *et al.* (2001) but not the stacking results. The results are shown in three sections of energy expenditure, perceived exertion and body discomfort and finally the LMM risk model.

7.3.1 Energy expenditure

The energy expended for cutting using the manual method can be seen in Table 7.1 and for using the harvester in Table 7.2. Table 7.3 shows the energy expended while using the staff implement in pulling. The results for topping and stacking can be seen in Appendix D. These were not included since they are not relevant to the Illovo Harvester but it was interesting to find that the stacking took on average less kJ per ton (903kJ.ton^{-1}) compared to cutting (1173kJ.ton^{-1}), which was not what previous studies have shown. As expected, topping was found to use the least energy per ton (464kJ.ton^{-1}).

Table 7.1 Results for energy expenditure in manual harvesting relating to output

NAME	WHR	pVO2	VO2	Energy Expenditure		Cane Cut	Energy per ton
	bt.min-1	ml/min/kg	l/min	kJ/min	kJ/shift	tons	kJ/ton
M1	95	11.63	0.69	14	3043	3.10	982
M2	123	19.26	1.11	22	6111	2.80	2182
M3	117	37.49	2.22	45	9012	6.40	1408
M4	107	9.40	0.50	10	1559	4.60	339
M5	133	14.09	0.88	18	3883	7.00	555
M6	117	27.34	1.62	33	5856	5.10	1148
M7	116	16.24	0.98	20	4134	3.10	1334
M8	149	27.58	1.60	32	1932	6.30	307
M9	110	19.95	1.43	29	5554	2.80	1984
M10	123	16.86	1.21	24	4170	2.80	1489
Average	119	20	1.22	25	4525	4.40	1173
Max	149	37	2	45	9012	7.00	2182
Min	95	9	1	10	1559	2.80	307
Std Dev	15	9	1	10	2208	1.70	643

Table 7.2 Results of energy expended during cutting using the Illovo sugarcane harvester

NAME	WHR	pVO2	VO2	Energy Expenditure		Cane Cut	Energy per ton
	bt.min-1	ml/min/kg	l/min	kJ/min	kJ/shift	tons	kJ/ton
M1	118.71	27.82	1.70	34.17	7852.36	8.90	882
M10	93.93	1.73	0.12	2.48	533.03	8.90	60

Table 7.3 Results of energy expended during using the staff to pull the cane while the cane was cut using Illovo sugarcane harvester

NAME	WHR	pVO2	VO2	Energy Expenditure		Cane Cut	Energy per ton
	bt.min-1	ml/min/kg	l/min	kJ/min	kJ/shift	tons	kJ/ton
M1	121.01	28.61	1.75	35.13	7546.59	8.90	847.93
M10	91.32	0.76	0.05	1.09	247.91	8.90	27.85

The predicted volume of oxygen consumed (pVO_2) was determined using the equation obtained from the linear regression of heart rates against the volume of oxygen expended. The outliers were removed due to the presence of experimental errors due to equipment errors. The graphs can be seen in Appendix D and it must be noted that subjects M2, M4 and M8 had low R^2 values (<0.55). This could result in the energy per ton for subject M2 to be skewed too high and too low for M4 and M8. Removing these values yields an average of 1271 $kJ.ton^{-1}$ for manual harvesting. The error band for the working heart rates (WHR) was found to be 119 ± 15 $bt.min^{-1}$ for cutting cane. The error band for the energy expended per ton was found to be 1173±643 $kJ.ton^{-1}$. M1 and M10 cut cane manually for the first time and were seen to be inexperienced. This however did not limit them since they performed as well as many seasoned cutters.

The results from using the ISH showed that there was no significant difference between the task of operating the machine (Table 7.2) and pulling the sugarcane with the staff (Table 7.3). M10 was seen to have a much lower average heart rate (94 $bt.min^{-1}$) compared to M1 (119 $bt.min^{-1}$) when harvesting with the ISH. This resulted in a large difference in the energy expenditure. M1 showed results that are to be expected whereas M10 low energy expenditure was unexpected. One reason was that the linear regression analysis did not test in the same range as experienced during the work shift. The lowest heart rate recorded in the step test was 95 $bt.min^{-1}$ with an average in the step test of 124 $bt.min^{-1}$. Also, due to the watch having to be strapped to the back of the subjects, it was not checked and hence it is unsure whether the watch was performing satisfactorily.

Due to the unrealistic results obtained for M10, a comparison with M1 was done for the ISH. For the cutting, M1 had a total expenditure of 7852 kJ that resulted in an output of 882 $kJ.ton^{-1}$. The average heart rate was seen to be 119 $bt.min^{-1}$ for cutting and 121 $bt.min^{-1}$ for pulling with the staff. This was unexpected and the staff task was perceived to be easier but it required similar energy requirements. Comparing M1 harvesting manually and harvesting with the ISH (Figure 7.5) shows that less energy was required to harvest a ton of sugar using the ISH. The average heart rates, however, were higher and show that the Illovo Harvester is better then manual harvesting from a production point of view but the higher energy consumption per day compared to manual harvesting will affect the worker negatively.

The responses suggest only one benefit of the Illovo harvester method which was the higher productivity (kJ per ton of cane cut). However, the heart rate, pVO2 and pEE data were all lower for the manual method. This conclusion was supported when comparing the cutters who had R^2 of greater then 60% (M1, M3, M5 and M6). A larger sample size with a higher degree of training in both tasks is required to make the results more conclusive.

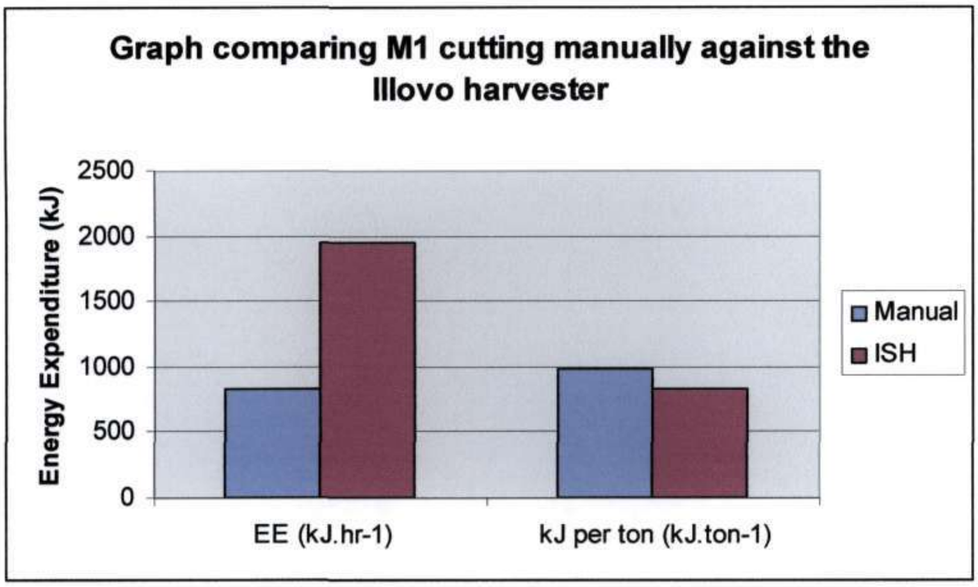

Figure 7.5 Comparison for cutter M1 for EE, and energy consumed per ton of cane cut

7.3.2 Body mass changes

The mass loss was measured by weighing the subjects before and after the workshift and the mass loss for both methods can be seen in Table 7.4. There was a much higher mass loss for the manual method of an average of 2.6 kg compared to only 1 kg for the ISH. It related to an average 4 % of the body mass weight loss for the manual cutting and 1.4 % for the Illovo harvester. The average fluid intake for manual harvesting was 2.2L and for the Illovo harvester was 0.5L (Appendix D). This shows that there was a much higher fluid loss during manual harvesting. Research shows that a loss of greater then 2 % can result in a decrease in physical and mental performance (McArdle *et al.*, 2001). This can be contributed to the ISH operators taking more frequent rests and drinks to re-fuel and change blades where as the manual workers drank large quantities infrequently.

Table 7.4 Weight loss during the work shift while harvesting manually

	Weight Before Kg	Weight After kg	Difference kg	Weight Loss %
Manual	65.0	62.4	2.6	4.0
Illovo Harvester	67.3	66.3	1.0	1.4

7.3.3 Perceived exertion and body discomfort

The average ratings of perceived exertion (RPE) can be seen in Table 7.5. In contrast to the physiological findings, RPE was slightly lower for the Illovo harvester. However, due to language and communication barriers this was deemed to not be very accurate. Since the two Illovo harvester operators had also experienced manual sugarcane cutting it was decided to compare these RPE ratings due to the operators having the same standard. This showed there was not a significant difference between manual and the Illovo system with ratings of 13.8 and 13.6 respectively. Generally, the RPE rating increased throughout the workshift and was probably due to the increase in temperature and the subjects taking more strain due to fatigue. The heart rate relating to the RPE showed an average of 124 $bt.min^{-1}$ to a 14.1 rating for manual harvesting. This shows that the equivalent heart rates that the subjects perceived the work as was approximately 140 $bt.min^{-1}$. The discrepancy can be related to the hot, uncomfortable and dirty conditions that the workers experience and as such, made them perceive the task to be more taxing than it was.

Table 7.5 RPE responses during manual harvesting compared to the Illovo harvester during the course of a shift

	Average Heart Rate (bt.min-1)	RPE
Manual	124	14.1
Illovo Harvester	-	13.6

The workers were also asked to rate the discomfort for manual harvesting and for the Illovo harvester in any area of the body using the Body Discomfort Scale seen in Table 7.6. The results indicate that discomfort was felt in different areas for the different methods, as expected. Care needs to be taken in reviewing these results since the subjects probably did not completely understand the concept. It does show however, that discomfort was experienced in 86% of the subjects in the lower back when harvesting manually and was clearly the prevalent area of discomfort. For the machine operation only one operator was evaluated showing that it was 100% of the work force. Obviously due to the sample size, this was not an accurate finding. Noteworthy was that more body areas were identified as experiencing discomfort during the manual method, with most rating the lower back as taking particular strain. With the harvester, discomfort was also experienced in the lower back and in particular the right upper extremity musculature due to the fact that they were manipulating the harvester on the right side of the body, and their thighs which was not rated during the manual method. This was likely due to their technique with the harvester during which the workers used the quadriceps musculature and torso to rotate the harvester from side to side.

Table 7.6 Body Discomfort Rating for manual sugarcane harvesting

Area of discomfort	Manual		Illovo Harvester	
	Number of Workers	Intensity of Rating	Number of Workers	Intensity of Rating
	(%)	(1-10)	(%)	(1-10)
Chest	43	5	0	0
Left bicept	29	3.5	0	0
Front of knees	14	5	0	0
Upper neck	14	4	0	0
Base of neck	29	4.5	0	0
Lower back	86	5	100	4
Right forearm	29	5	0	0
Right hand	14	5	0	0
Front right shoulder	0	0	100	5
Right bicept	0	0	100	5
Left and Right Thighs	0	0	100	4

7.3.4 LMM risk model

In contrast to the physiological findings, the results of the LMM suggest that the harvester was a superior method compared to the manual method, particularly with regard to the strain placed on the lower back. Figures 7.6, 7.8 and 7.9 show the results during cutting sugarcane for the Illovo cutter and for manual.

Figure 7.6 shows that when cutting manually, the back goes through a larger range of movement compared to the Illovo harvester. This was expected due to the manual harvester having to stoop and the Illovo harvester standing fairly erect as seen in Figure 7.7. There were large differences in the amount of movement; this can be seen in Appendix D, Figure D12 shows more peaks of movement for a similar time period for manual harvesting. The largest difference was the maximum flexion with a difference of 25 degrees and the lateral range having 20 degrees more range than the Illovo cutter. The only values that were similar were the maximum right twist.

This was interesting due to the fact that when using the Illovo cutter, the operator cuts from right to left using a left twist. This shows that when cutting the operator doesn't use his back but rather his thighs for leverage and the twisting occurs when bringing the machine back. This was only determined once the LMM was initiated during cutting and the results were analysed. This shows the importance of doing a thorough study of a particular job description.

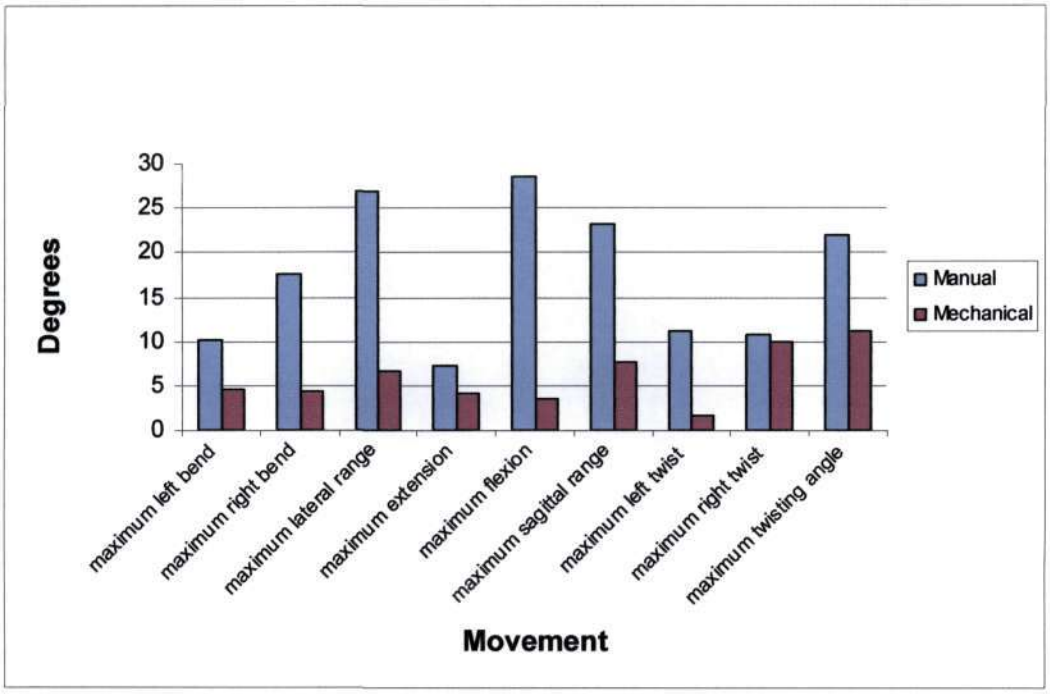

Figure 7.6 Comparison between the manual harvesting method and the Illovo harvesting method for the different movements of the lower back shown in degrees

Figure 7.7 Different postures taken for the different cutting methods with the LMM attached showing the Illovo harvester was able to stand erect unlike the manual harvester

Figure 7.8 shows the speed or velocity of movement and again it was found to be much higher with the manual system due to the use of the back to move the blade quickly in order to be able to do a clean, pure impact cut. The average velocities for the three primary movements were all similar with the Illovo harvester and were all ± 3 degrees/sec compared to the average for manual harvesting between 11 degrees/sec for the lateral velocity and 19 degrees/sec for the twisting velocity. In Appendix D, Figure D13 shows that when harvesting manually the lower back experiences periods of high peaks followed by a periods of low peaks which are associated with walking forward to the next stool to commence cutting. The Illovo cutter experiences a more constant peak formation that shows a more even distribution with the lower back experiencing a more constant velocity.

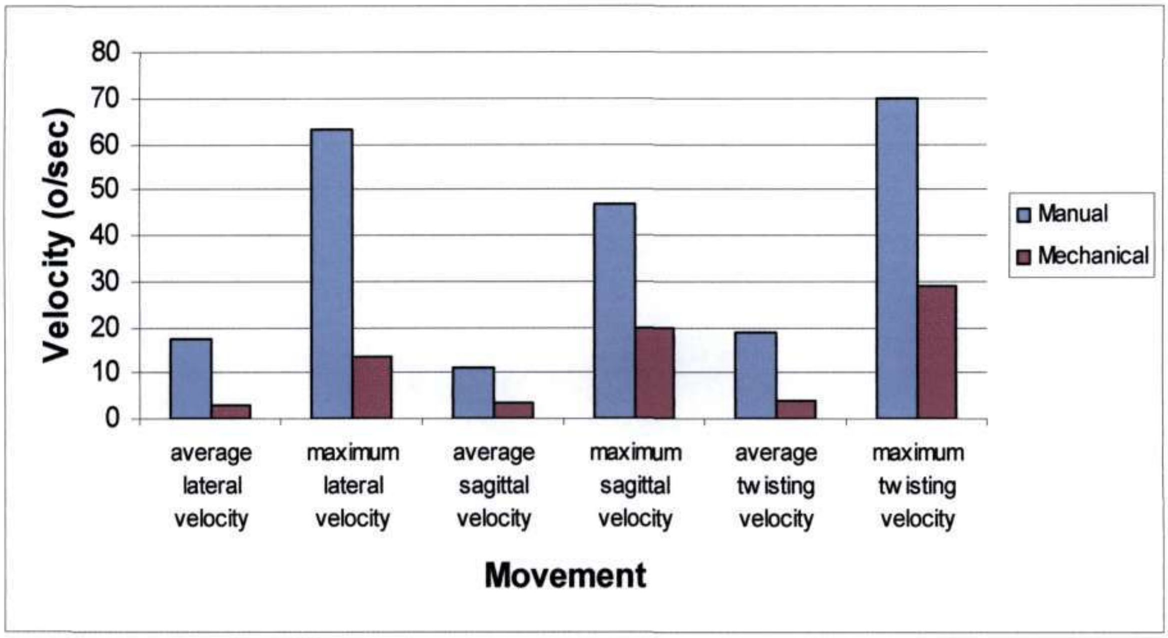

Figure 7.8 Comparison between the manual harvesting method and the Illovo harvesting method for the velocity of the lower back shown in degrees.sec^{-1}

Figure 7.9 shows the acceleration of the back in harvesting. This again shows how quickly the labourer was required to accelerate and decelerate with manual harvesting. The maximum lateral acceleration for the lateral acceleration was 6 times greater when harvesting manually and approximately 3 times greater for the maximum sagittal and twisting accelerations.

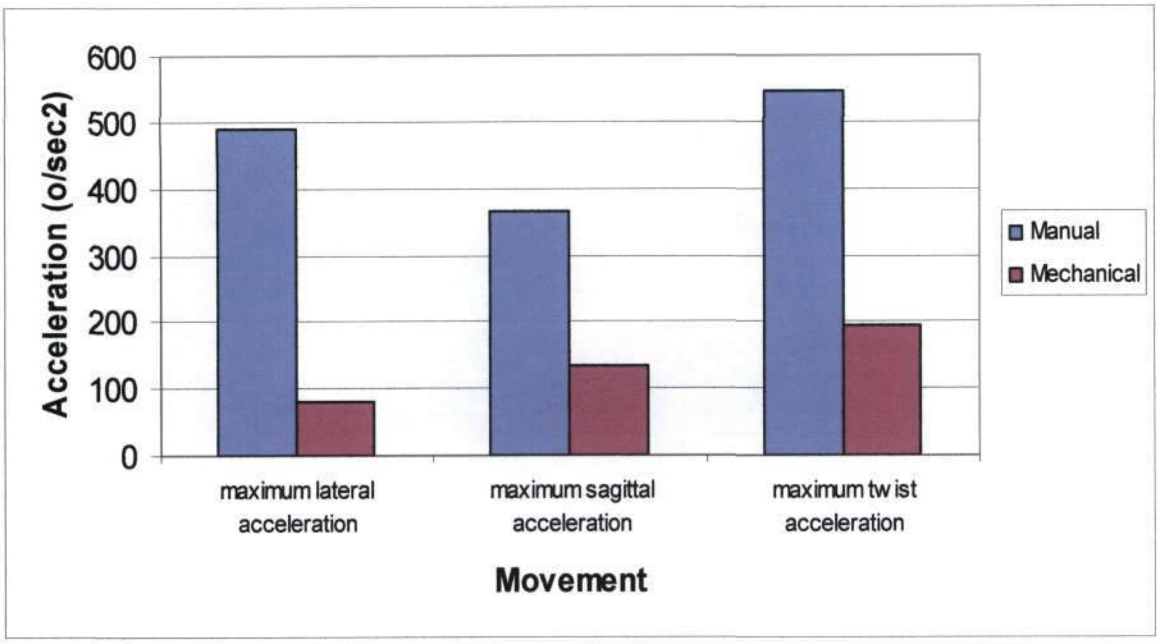

Figure 7.9 Comparison between the manual harvesting method and the Illovo harvesting method for the acceleration of the lower back shown in degrees/sec^2

Figure 7.10 shows the results superimposed on Figure 6.5 to indicate the probability of being in a high risk group having ≥12 incidences/200 000hrs. Figure 7.10 shows the distributions with the black line representing manual harvesting and the blue line representing the Illovo harvester.

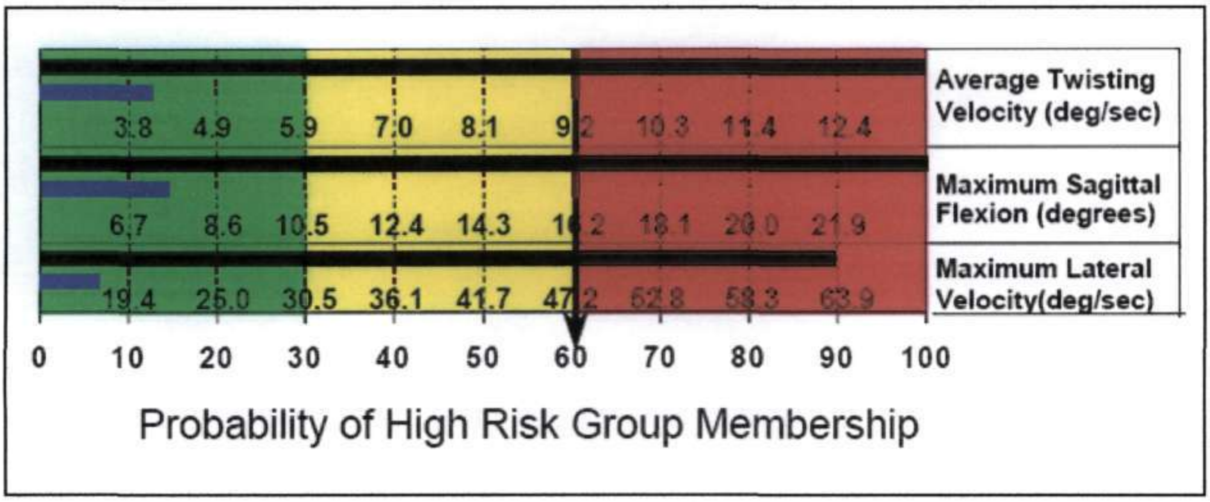

Figure 7.10 Probability of the different methods being classed in a high risk group with the black bar being manual harvesting and the blue bar being the Illovo harvester

The results for manual harvesting for average twisting and for the maximum sagittal flexion reached full scale and relates to a 100% probability of falling in the High-risk group and the maximum lateral velocity of 63.18 $degrees.sec^{-1}$ relates to a 90% probability. This shows that manual harvesting falls in the High-risk category and was likely to cause lower back disorders with prolonged working under these conditions. For the Illovo harvester (blue bar) it falls in the Low-risk region with probabilities of approximately 12%. These results indicate that using the Illovo harvester puts very little stress and strain on the lower back and is not likely to be a determining factor in acquiring a lower back disorder.

7.4 Conclusion

The results suggest that the Illovo cutter requires less energy per ton and was seen to be more energy efficient compared to the manual harvesting method. However, from an overall physiological perspective, workers using the Illovo cutter took more strain. Hence, although less energy was expended per ton, more energy was expended overall during a work shift. This shows that it may be beneficial for productivity but not for the worker. This could however change with refinements to the harvester (making the blade and machine lighter) and more training for the workers (use the correct harvesting techniques). It should be noted that due to limitations in sample size it will require further testing with a larger sample size to determine the harvested output per kJ more accurately. The RPE was lower for the Illovo harvester but there was a significantly lower weight loss compared to the manual system. This was possible due to the workers being forced to have a break to re-fuel and change the blades on the machine where they drank water and replaced lost fluids. The body discomfort showed that the manual workers suffer the most from lower back pain and chest pain. The Illovo harvester also creates discomfort in the lower back, and in the thighs as well, thus showing which muscle groups were used in operation. The LMM risk model shows the Illovo cutter falls into the Low-risk group compared to the High-risk group for the manual harvesting. As a whole the Illovo harvester is a better system with regard to the ergonomics.

8. DISCUSSION, CONCLUSION AND RECOMMENDATIONS

8.1 Discussion and Conclusions

A farmer does not obtain any profits while the crop is standing in the field and so harvesting is clearly an integral part of agriculture where manual harvesting is the dominant method of harvesting sugarcane in South Africa. Crop losses incurred during manual harvesting are still less than those of the mechanical harvesters and by following good management practices this trend should continue. However, with a decreasing labour force willing to manually harvest sugarcane, it is necessary to recognise that mechanisation will have to be gradually implemented. The available, fully mechanised systems (chopper harvesters) have many disadvantages that include the inability to harvest on steep slopes and require a high capital outlay. Hence, new methods of cutting need to be developed and analysed to improve efficiencies and supply high quality sugarcane that is fresh and that has minimal extraneous matter. These new harvesting methods need to supply an intermediate step between manual and fully mechanised harvesting systems.

Harvesting sugarcane requires an implement that cuts the cane efficiently. The manual and chopper harvesting method both use a 100 % impact cut when harvesting sugarcane. However, literature showed that the overall optimal blade angle to harvest sugarcane was a blade that is 22.7 degrees to the tangent which has a ratio of 75 % slicing to 25 % impact cutting. It has the least losses and does the least damage to the cane. A blade with these features was designed and fitted to a commercially available STIHL brushcutter and evaluated for cutting sugarcane.

Numerous variations of the blade were designed and tested, where each had its own advantages and disadvantages. A compromise had to be reached to make the blade economically viable while still able to harvest sugarcane efficiently and effectively. Design D as a whole performed the best and met the majority of the criteria. It consisted of a main base plate with four replaceable edges that could be used for four cuttings, one on each edge. It had a 45 degree to the tangent cutting angle, this was larger than the 22.7 degrees to reduce the rate of wear of the blade. It was noted that the 22.7 degree blade cut sugarcane with the least damage and was the safest but was not economically viable due to high wear rates. Design D had a final wear rate of 0.4 $g.min^{-1}$, lasted

308 min and cut 16 tons of sugarcane before it required replacement. Losses incurred during harvesting because of lost cane amounted to R251.ha^{-1} and is R28.ha^{-1} less then the conventional manual method. The major disadvantage of Design D was the mass of the blade of 2.05 kg. This should ideally not exceed 1.5 kg so as not to overload the motor or cause the gearhead to slip off the shaft.

The STIHL FS 500 brushcutter was chosen but required a few adaptations for it to last. It required a more robust filter system that could handle the harsh operating conditions. Other adaptations included a spacer where the blade was attached to be able to cut the stick as low as possible and a grub screw inserted through the gearhead to stop the gearhead slipping off the drive shaft. The machine was unable to last a full season mainly due to the drive tube and shaft bending. With a few more minor adaptations this should be alleviated. Another well known model was tested, but, was found to be less robust than the STIHL.

Once the ISH was designed and adapted, it was necessary to integrate it into the existing harvesting and transport practices. The Illovo sugarcane harvesting system which was developed comprised of two trained operators operating one machine and a staff at a time that cut and lay the sugarcane into windrows. They were followed by another two unskilled labourers who topped and stacked the cane into 4 ton bundles. The operators were split into a puller and a cutter. The puller used a shepherd's crock/staff to pull the cane toward the windrow while the cutter cut in a sweeping motion from right to left. The Illovo sugar harvesting system used two basic systems called System 1 and System 2. System 2 cut in a block formation and was the more efficient system but could not operate on steep slopes (> 75 %), and although System 1 was less efficient, it was recommended for steep areas.

With experience and development, the performance of the ISH improved mainly because of the downtime that was reduced from 42 % in 2005 to 29 % in 2006. This was attributed to the implementation of two extra machines that rotated during the work shift. The output during 2006 was 13 t.day^{-1} with a machine output of 3.05 t.hr^{-1}. The best results achieved were 19.6 t.day^{-1} with a machine output of 4.59 t.hr^{-1}. The extra capital cost was minimal compared to the saving from the labour being more productive and having less downtime. The downtime was however, still too high and it was decided that a task system should be implemented where the Illovo sugarcane harvesting team is tasked a set amount to cut per day. This in parallel with good training and supervision will increase the productivity and decrease the downtime and stoppages caused by breakages.

The cost of operating was approximately R15.84.t^{-1} and was competitive compared to the conventional manual harvesting. The cost could be expected to reduce further with the implementation of a full system where one would benefit from experience and economics of scale. Estimated reduced values were approximately R14.72.t^{-1}. Labour costs contributed the most at 65 % followed by fuel (17 %), blades (10 %), maintenance (5 %) and capital outlay (3 %).

Safety was a concern but by supplying adequate safety equipment and with good supervision, no injuries should occur. The most dangerous task was that of the puller, it was important that he remain alert and this is achieved by regular changing between tasks of cutting and pulling.

The system is a viable option with a decreasing labour force, because the task of cutting sugarcane would become more attractive and the status of sugarcane cutting elevated. More work, however, needs to be done to decrease downtime, improve management, implement a change management system and convince labourers and farmers of the advantages of the system. A further ergonomic study was required to determine whether the system had any benefits for the worker from a physiological point of view.

Ergonomics is the study of work and systems that involve humans and machines. The objective is to maximize productivity by using the body more effectively, reducing operator fatigue and discomfort and so improve the efficiency of the worker. The ergonomic study compared the ISH to the conventional manual harvesting system. The data suggests that the Illovo sugarcane harvester uses less energy per ton and was seen to be more energy efficient compared to the current manual harvesting method. Although less energy was expended per ton, more energy was still expending overall i.e. per shift so it may be beneficial for productivity but not for the worker. This could however change with refinements to the harvester (making the blade and machine lighter) and more training for the workers (using the correct harvesting techniques). It should be noted that due to limitations in sample size, further testing should be carried out with a larger sample size to accurately determine the harvested output per kJ. The LMM risk model showed that the Illovo cutter fell in the Low-risk occupation group compared to the High-risk group for manual harvesting. As a whole the Illovo harvester was a better system with regard to the ergonomics.

The Illovo sugarcane harvesting system, like any harvesting system, has many advantages and disadvantages. The advantages are that the ISH can operate on steep slopes, it cuts the cane low and cleanly, harvests cane at a faster rate compared to manual harvesting, and raises the standard and status of the sugarcane harvester that should create a larger labour pool to draw from. The disadvantages are that it is more labour intensive, it experiences a high amount of downtime due to machines breaking, there is a high rate of blade wear, and the system requires double handling of the cane. However, with further research and training these disadvantages should decrease making the ISH a feasible solution to harvest sugarcane.

8.2 Recommendations for Further Research

Recommendations are for further work to be done on the blade, machine, system and ergonomic study and are shown below.

BLADE

The blade should be lighter and wear at a slower rate. This could be achieved by drilling larger holes in the base plate and in the replaceable edges. Slower wear rates might be achieved with exotic metals but will increase the cost.

The connectors should be adapted to reduce the size of the bolt heads protruding that cause damage to the cane and excessive debris. This can be achieved by using rivets alleviating the need for bolts and the problems caused by the thread.

MACHINE

The machine needs to be more robust. Especially along the drive shaft and tube that is the most susceptible to damage caused by the heavy blade and nature of harvesting. This can be done by inserting a rib along the outer drive tube to make it more rigid. The filter system works adequately, but further work with a snorkel system might significantly increase the life of the engine.

SYSTEM

Manpower is the highest cost and work should be done to improve their productivity. One way is to implement the task system and decrease the double handling of the cane. Another way is to the further development of a pre-topper.

ERGONOMIC STUDY

A more thorough study is required using a larger sample size that would give a more accurate value for the energy expenditure. More training is recommended using the system. This will probably decrease the energy expenditure since the body will be more accustomed to the operation.

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APPENDIX A

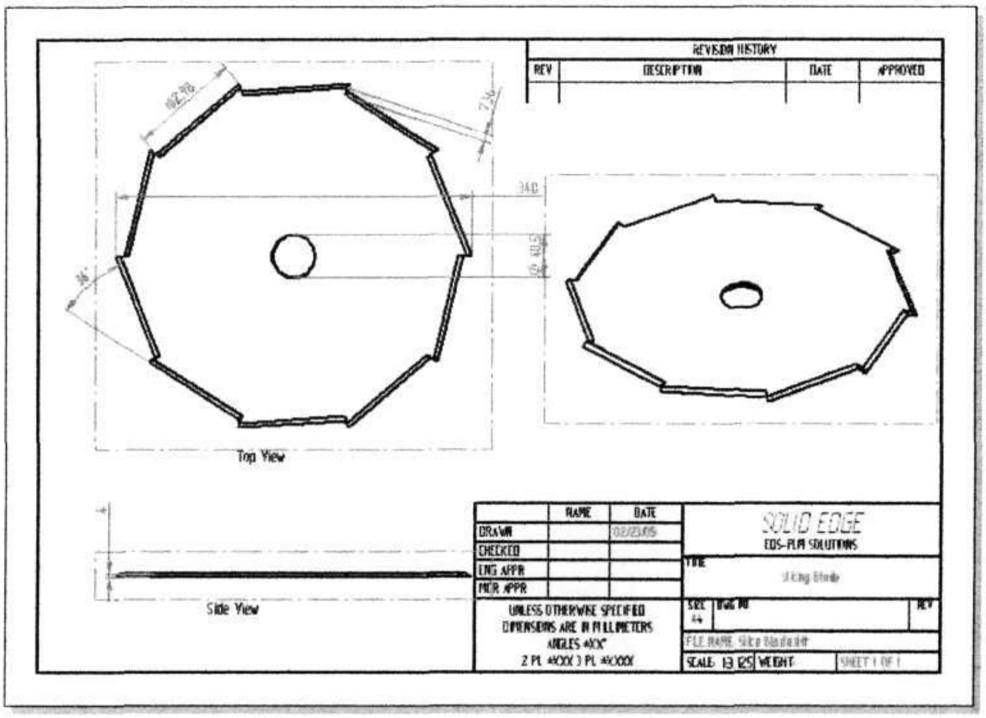


Figure A1: The base blade and design A dimensions.

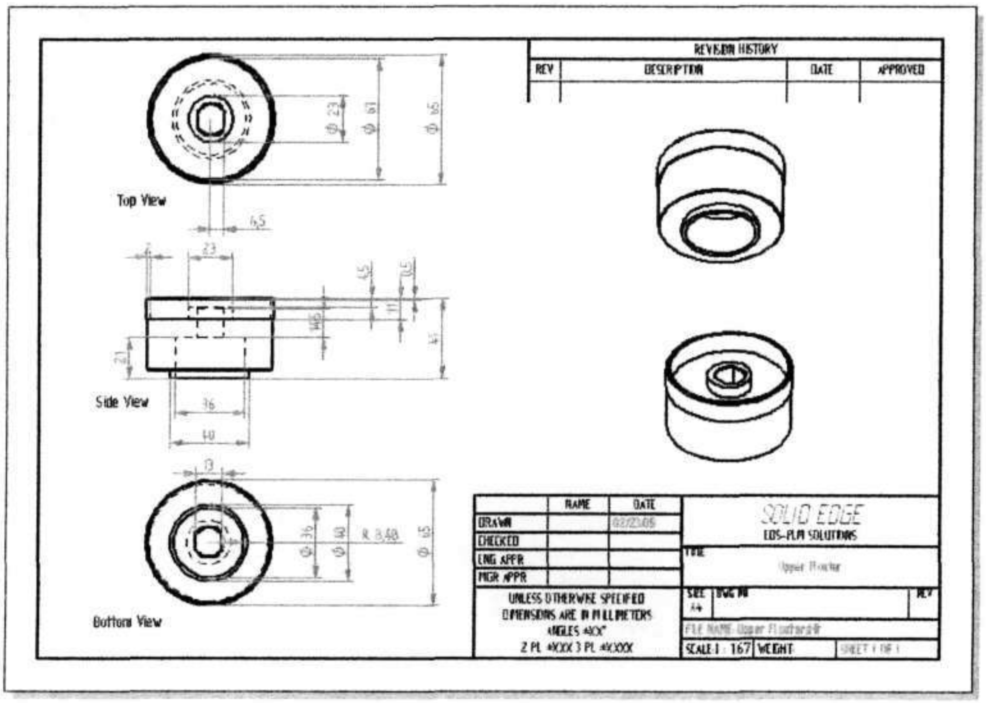


Figure A2: Upper spacer

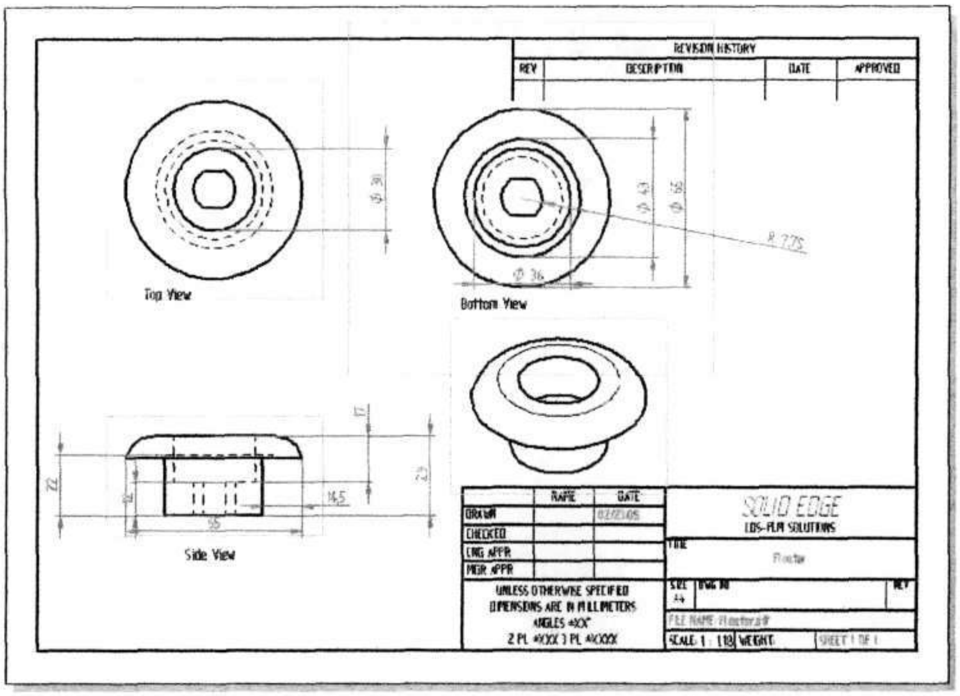


Figure A3: Lower floater

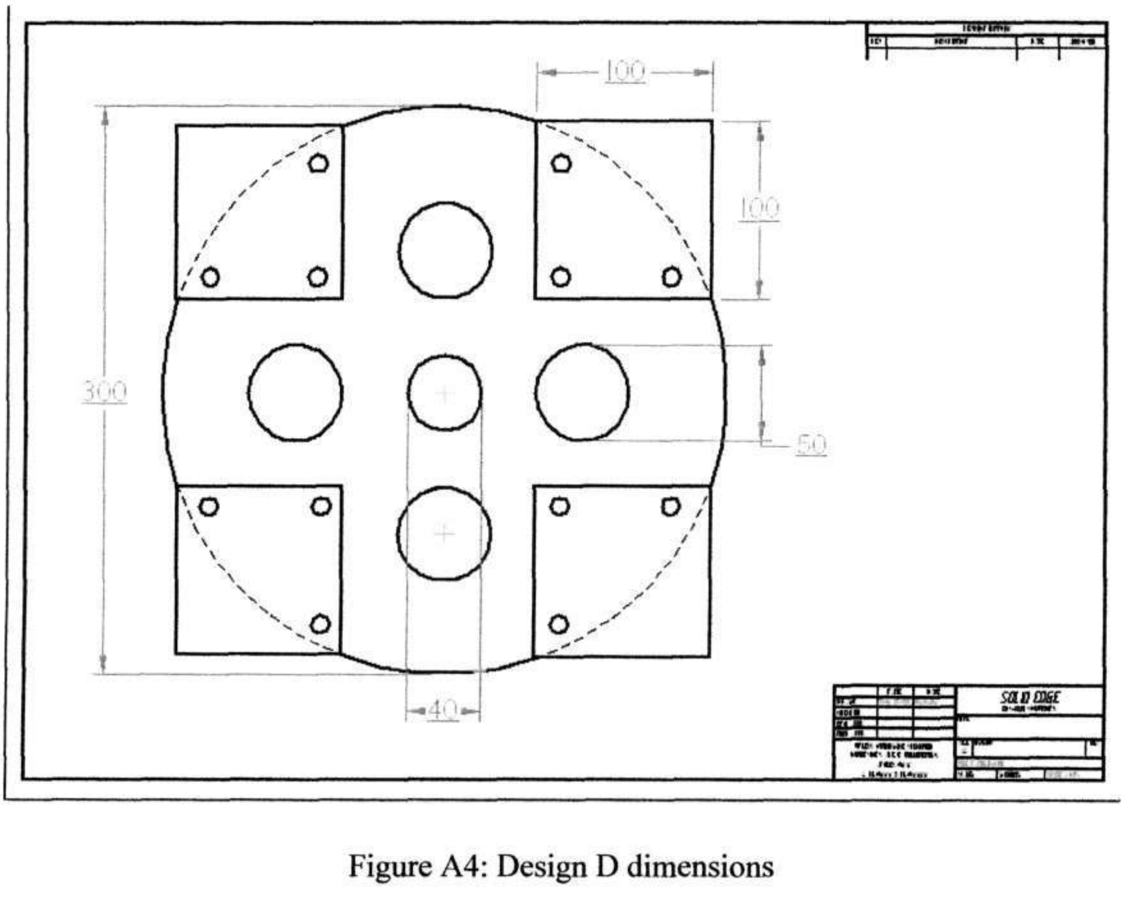


Figure A4: Design D dimensions

APPENDIX B

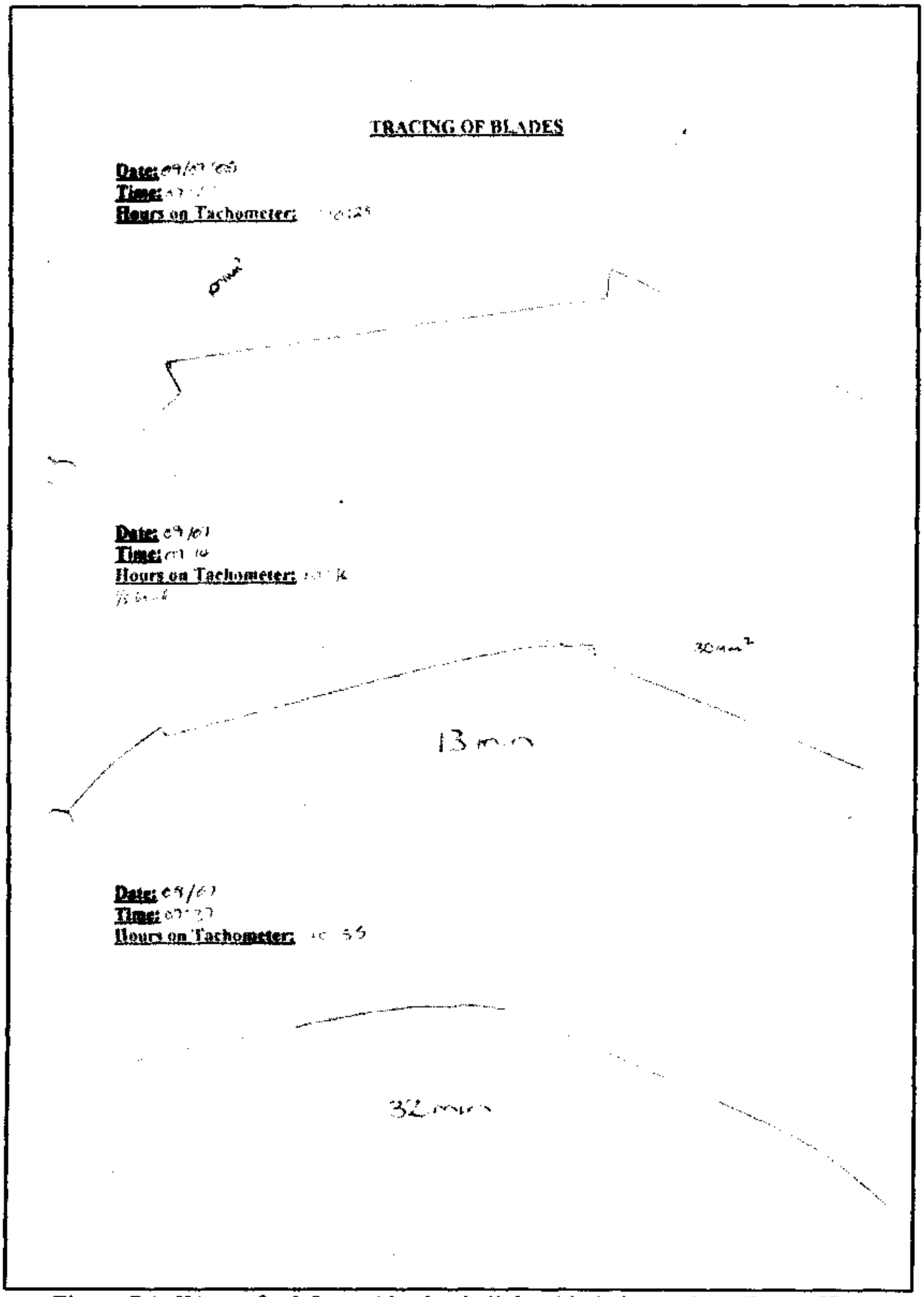


Figure B1: Wear of a 2.8mm 10 edged slicing blade in sandy soils at 45Rc.

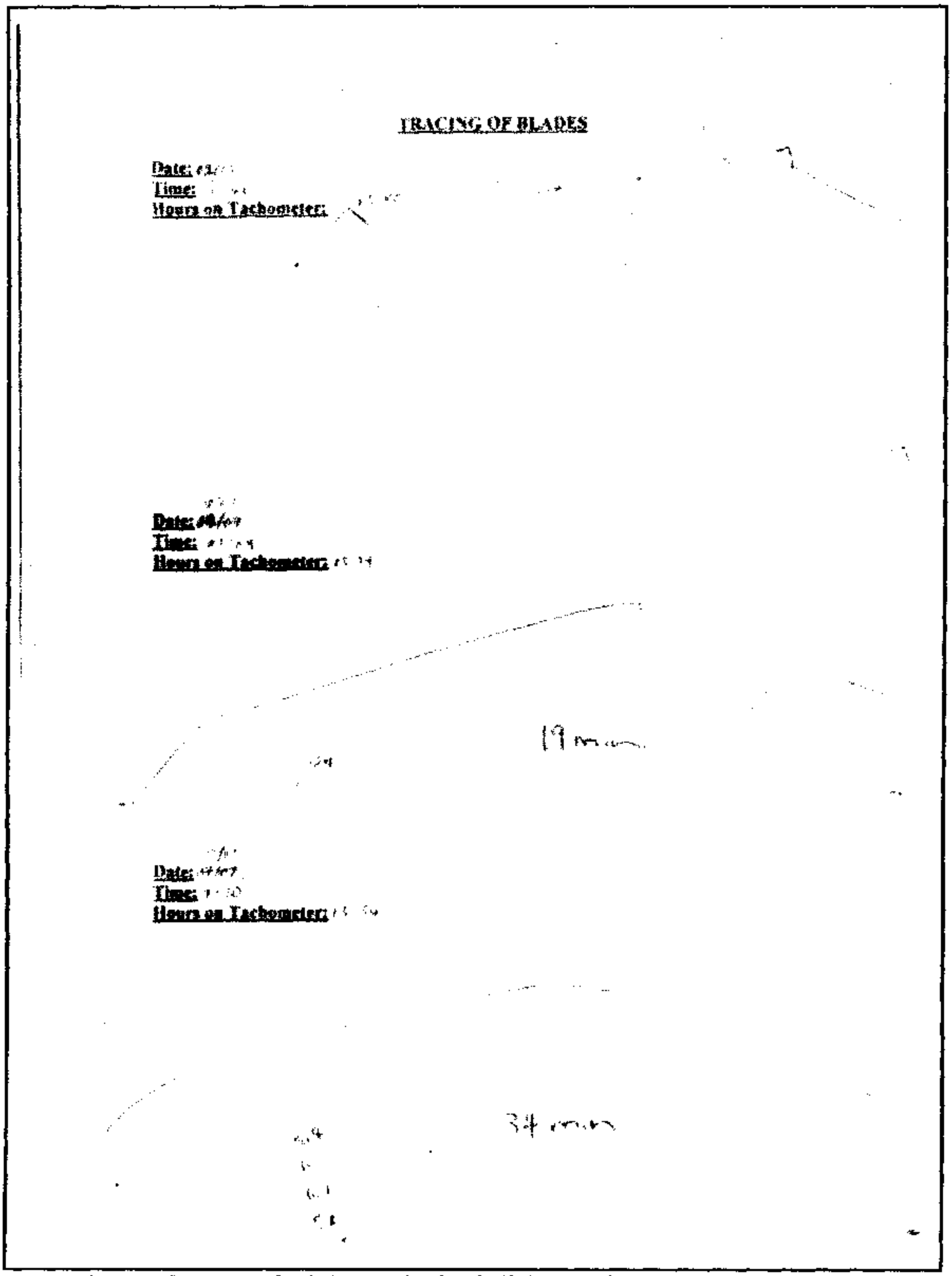


Figure B2: Wear of a 2.8mm 10 edged slicing blade in sandy soils at 48Rc.

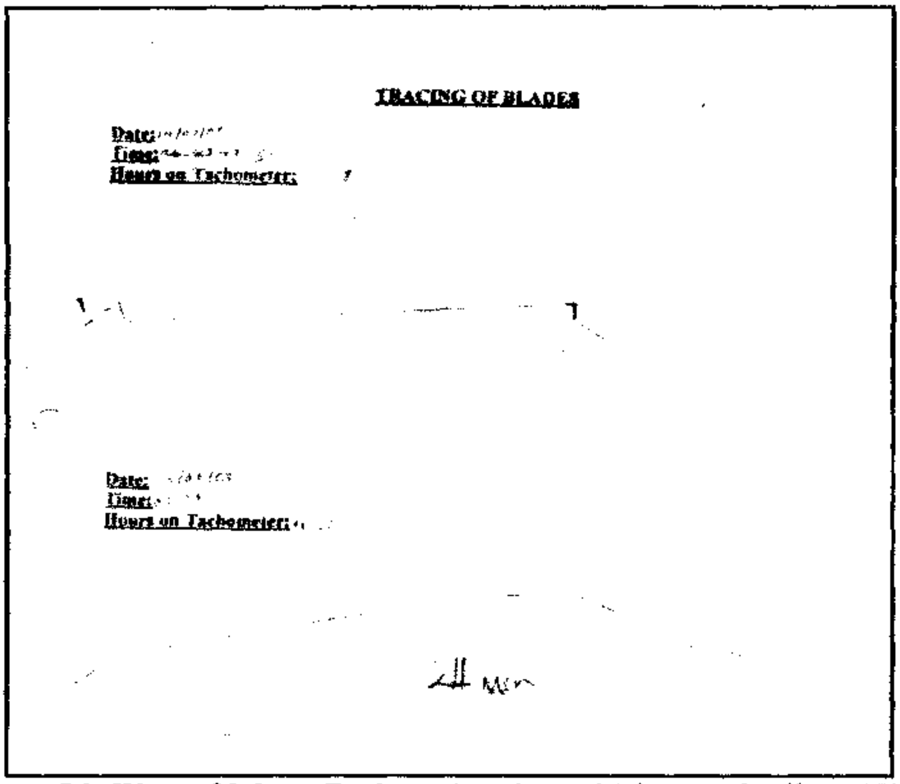


Figure B3: Wear of 2.8mm DesignA (exotic steels) in gravel soils at 45Rc.

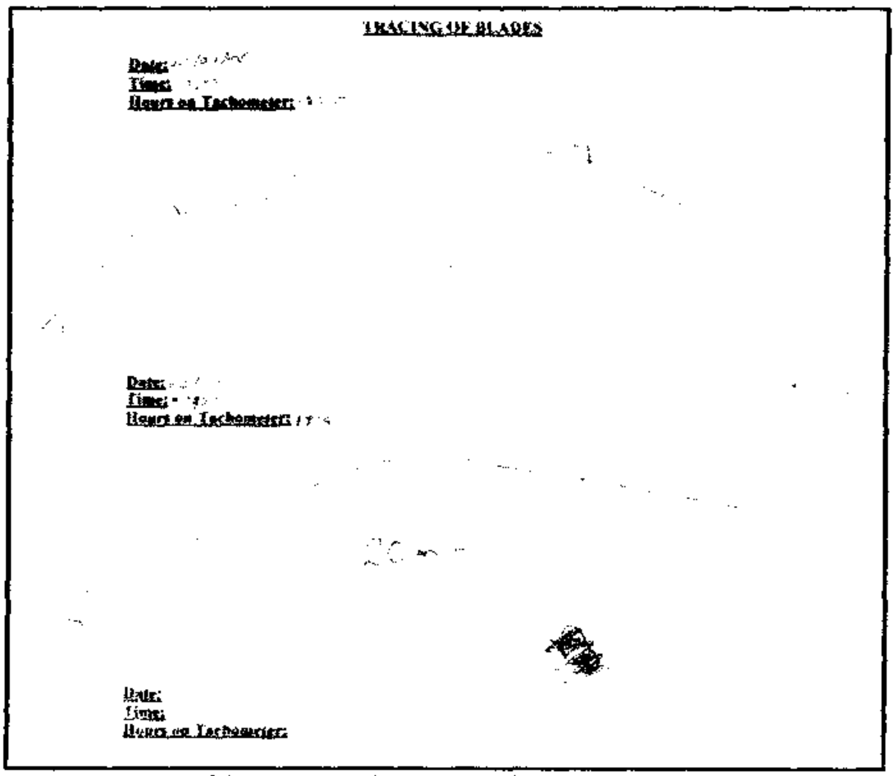


Figure B4: Wear of 2.4mm DesignA (exotic steels) in gravel soils at 45Rc.

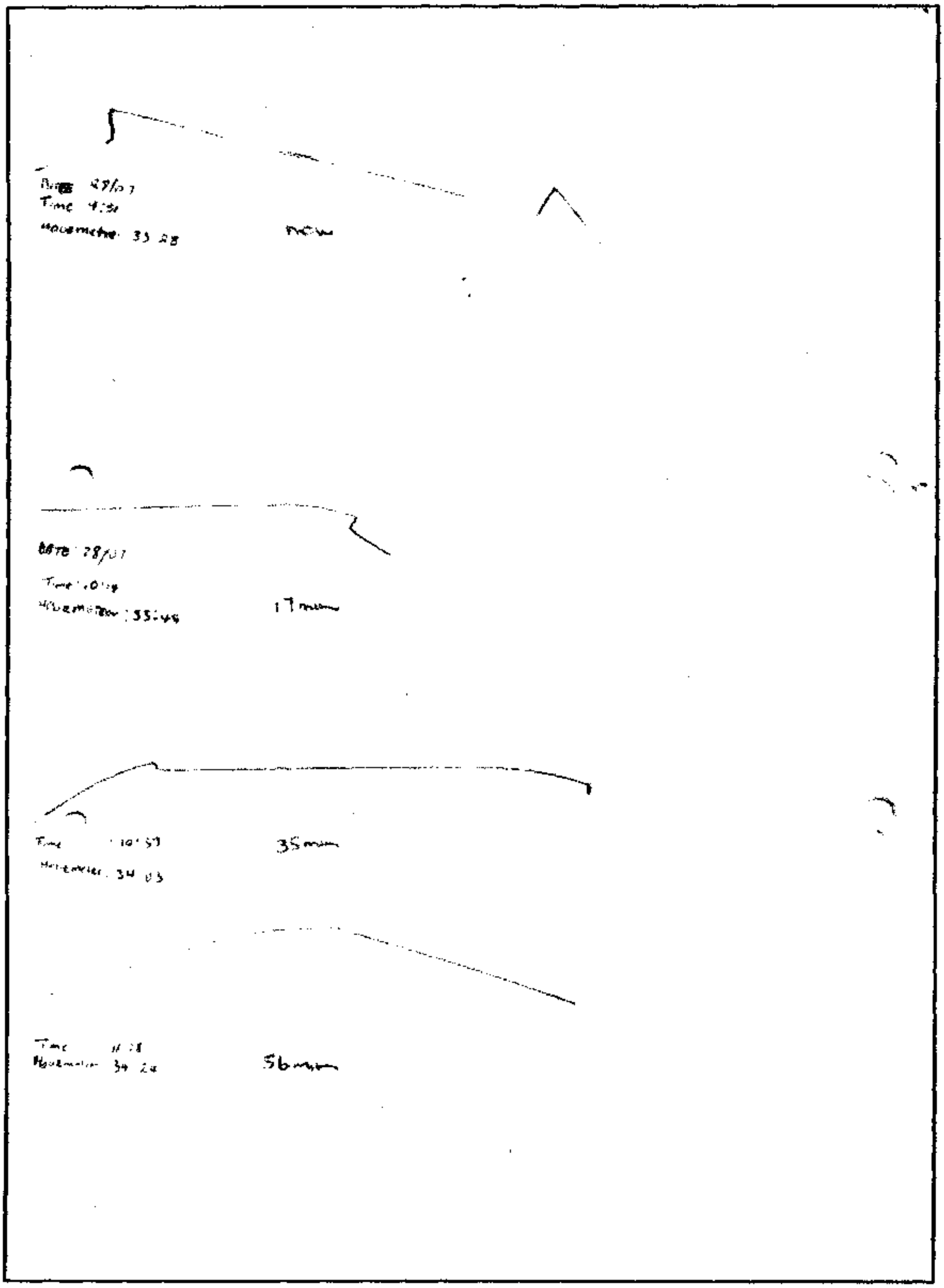


Figure B5: Wear of 2.8mm Design A in a clayey soil with no stones.

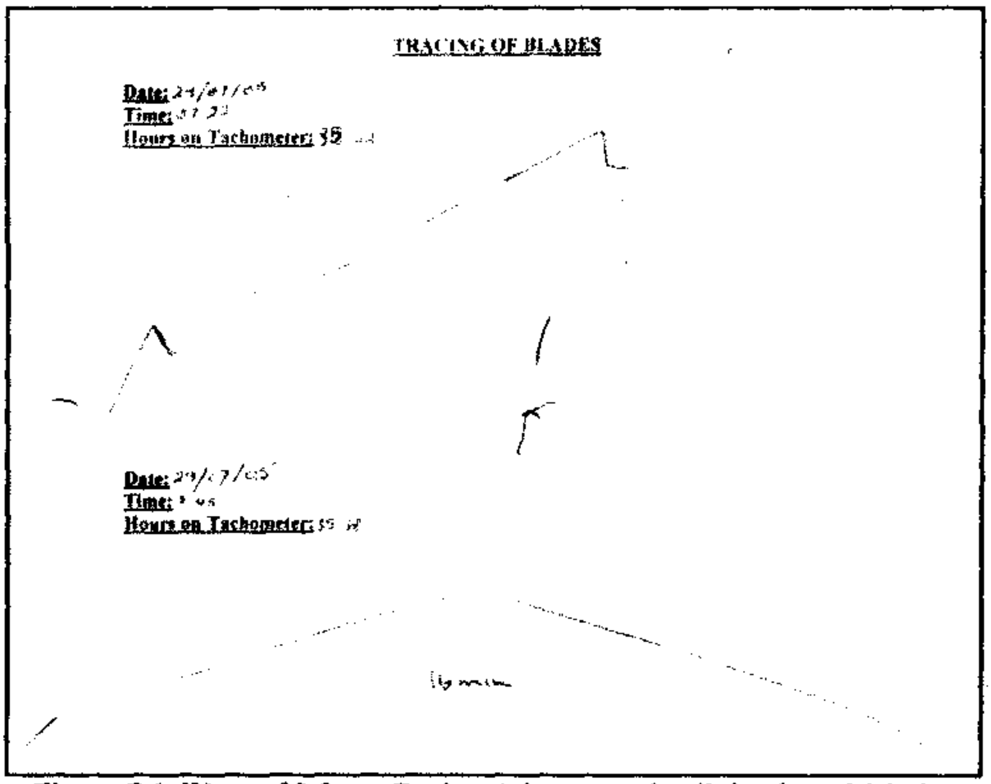


Figure B6: Wear of 2.8mm Design A in a gravel soil that lasted 16min.

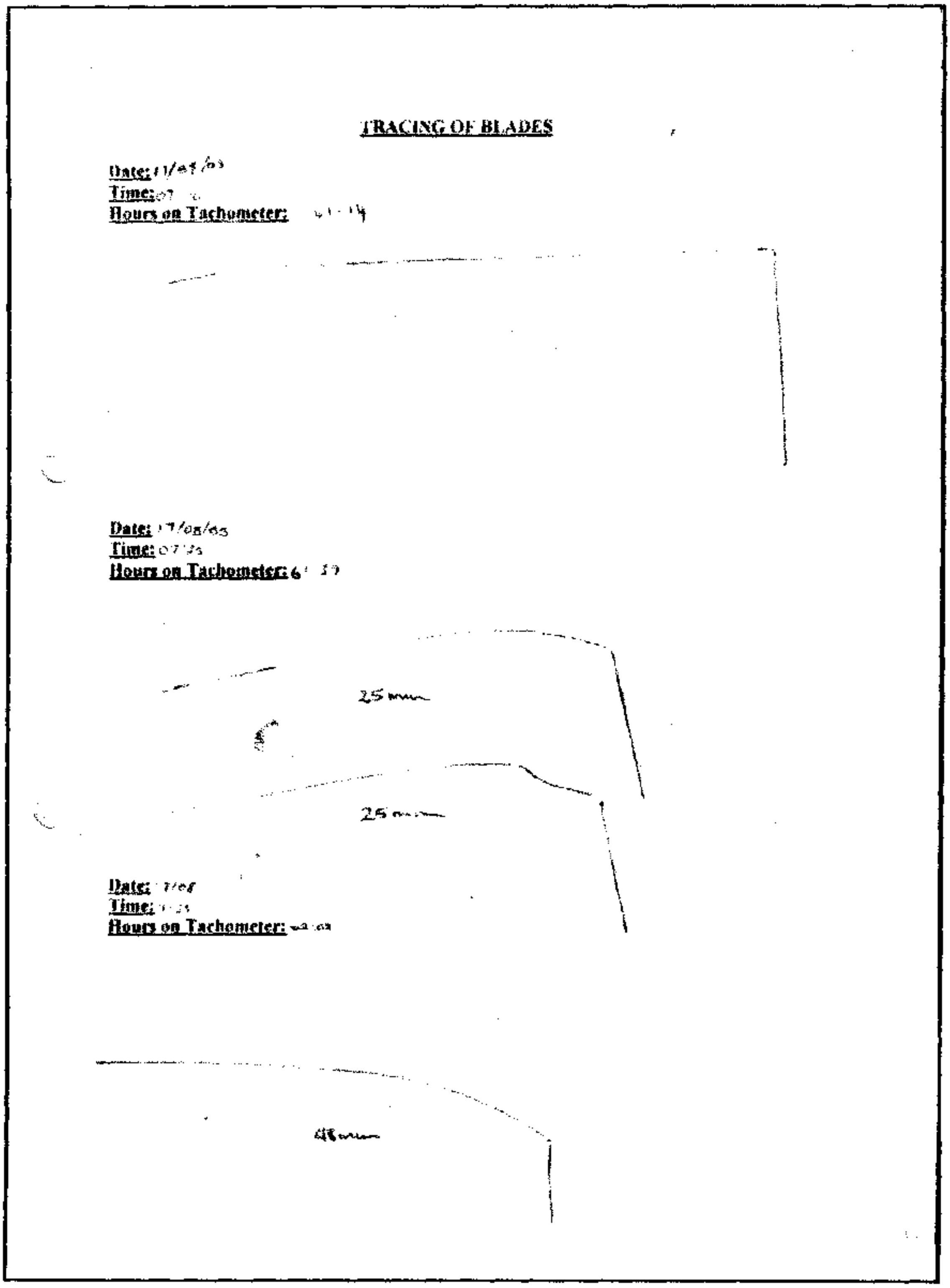


Figure B7: Design C hardened to 48Rc showing wear in a sandy soil.

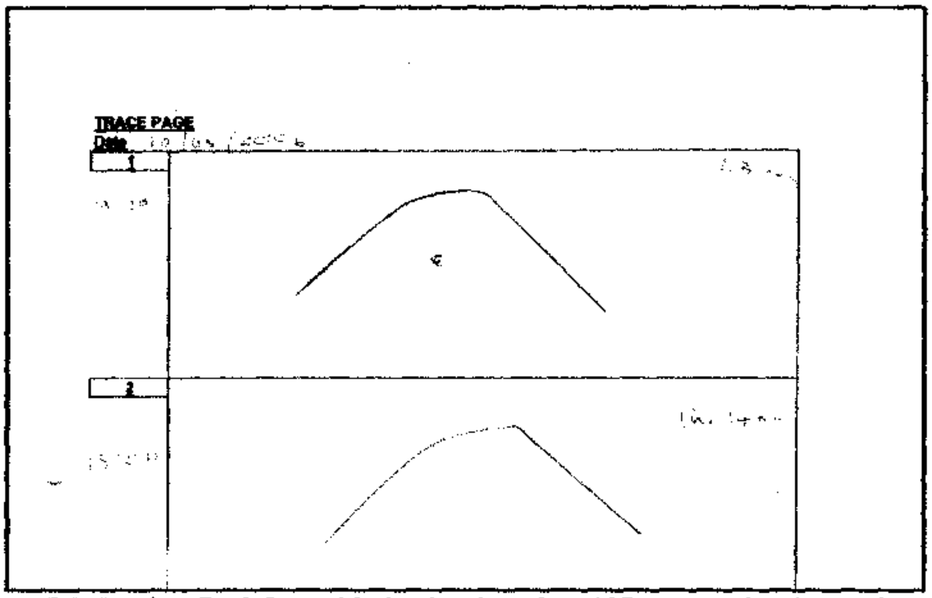


Figure B8: Design D, 2.8mm blades hardened to 48Rc operating in sandy soils.

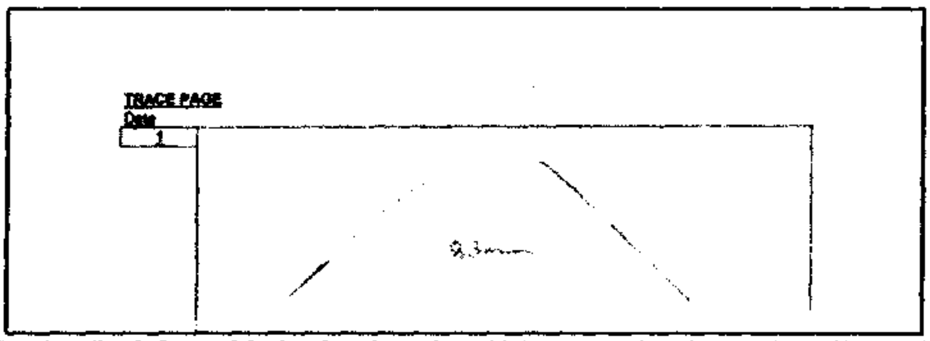


Figure B9: Design D, 2.8mm blades hardened to 48Rc operating in sandy soils on the 11th May 2006.

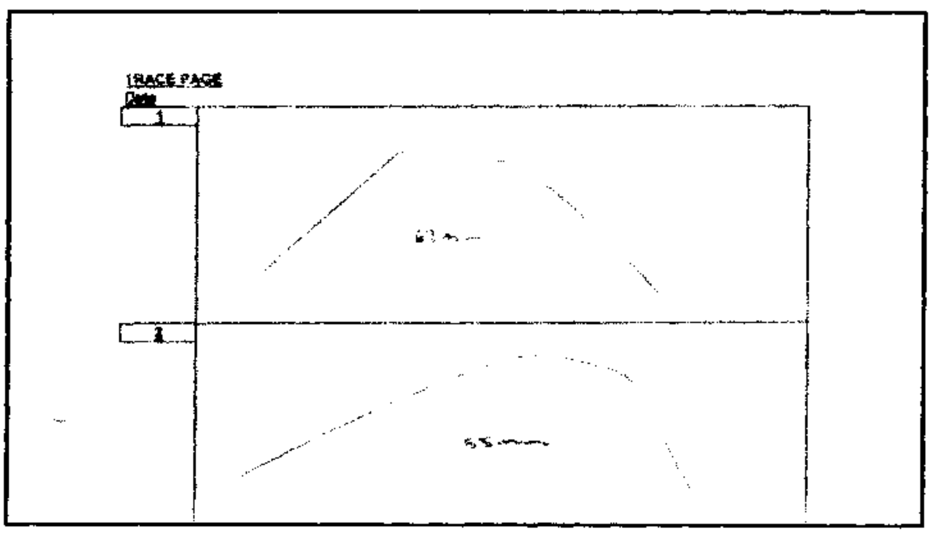


Figure B10: Design D, 2.8mm blades hardened to 48Rc operating in sandy soils on the 17th May 2006.

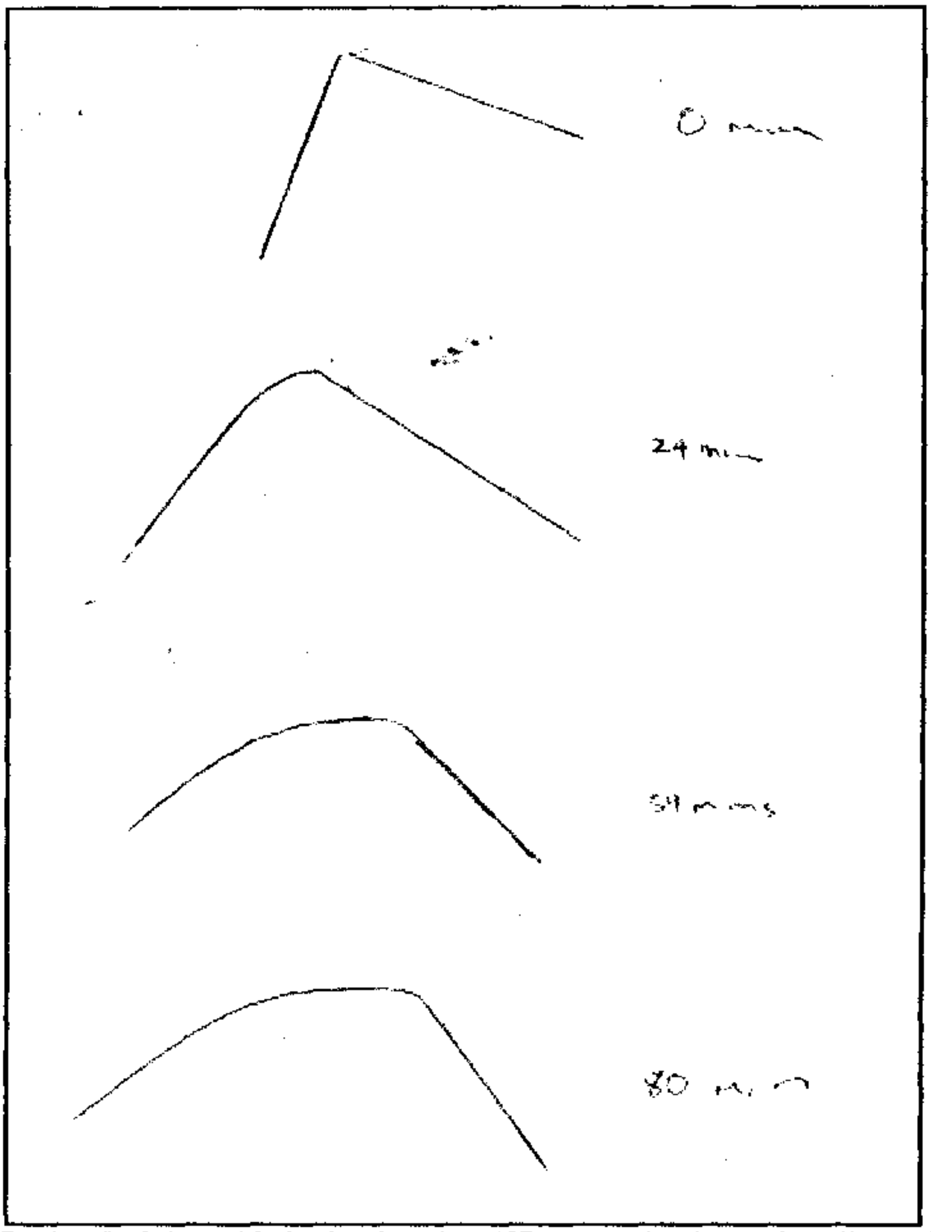


Figure B11: Design D, 2.8mm blades hardened to 48Rc operating in sandy soils on the 18th May 2006 showing the progression of wear.

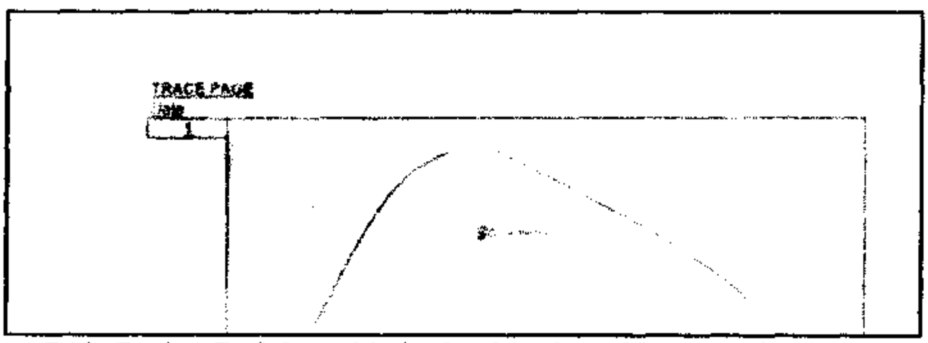


Figure B12: Design D, 2.8mm blades hardened to 48Rc operating in sandy soils on the 23rd May 2006.

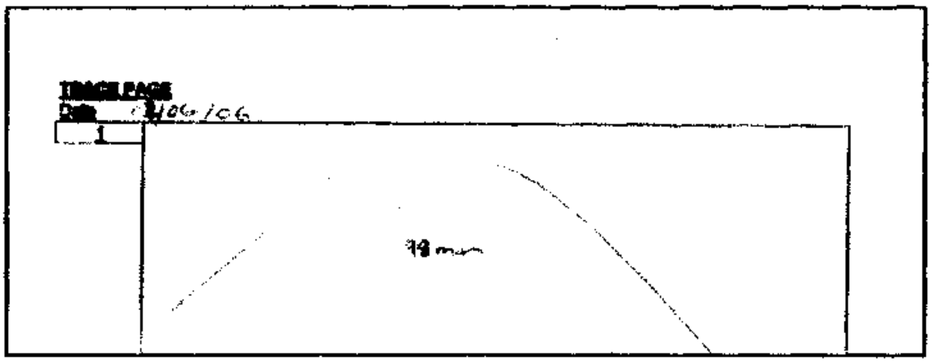


Figure B13: Design D, 2.8mm blades hardened to 48Rc operating in sandy soils cutting N39.

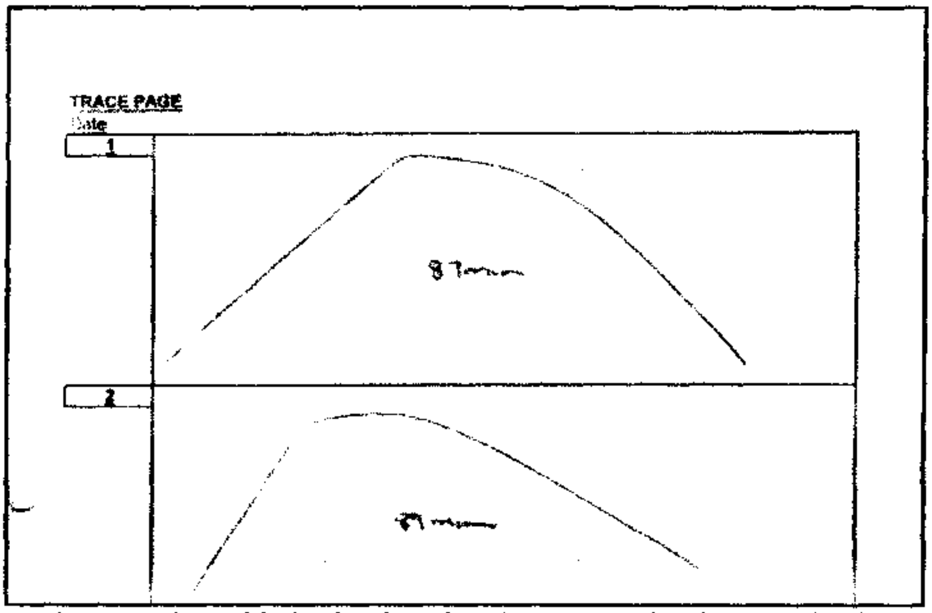


Figure B12: Design D, 2.8mm blades hardened to 48Rc operating in sandy/rocky soils on the 9th June 2006.

APPENDIX C

Table C1 Time and motion study sheets

TIME AND MOTION STUDY

Date	
Time Start	
Time End	
Machine Tacho Start	
Machine Tacho End	
Total Time machine Run	
Walking with machine running	
Time Cutting	
Re-fueling	
Blade Change	
Filter change	
Operator change	
Rest/water break	
Other Stoppages	

Table C2 Infield measurement sheets

FIELD TRIAL MEASUREMENTS

General

Date	
Harvesting System	
Field number	
Yield	
Type of Cane	
Slope %	
Ground conditions (wet/dry)	
Ground Conditions (stones)	
Comments	

Time and Fuel

Hour meter (start)	
Hour meter (end)	
Total hours worked	
Start work (time)	
Knock off (time)	
Total hours in field	
Litres of fuel used	

Machines

	STIHL 1	STIHL 2	HUSQ
Usage	-	-	-
	-		-
Re-fuels			
Time per re-fueling			
Filter changes			
Number of blades			

Blades

Number of blade breakages			
Reasons			
1. Hour meter start			
1. Hour meter end		blunt	broken
2. Hour meter start			
2. Hour meter end		blunt	broken

Table C3 Human discomfort and safety analysis sheets

Personal Questionaire

Date				
Name				
Hours worked with machine				
Hours doing other work				
Are you tired after working with the machine?	No	Slightly	Tired	Very tired
Are you tired after doing other work?	No	Slightly	Tired	Very tired
Any pains?	Yes	No		
Where?	upper body	torso	lower body	
Specific Injury				
How much liquid intake?				
Comments				

Personal Questionaire

Date				
Name				
Hours worked with machine				
Hours doing other work				
Are you tired after working with the machine?	No	Slightly	Tired	Very tired
Are you tired after doing other work?	No	Slightly	Tired	Very tired
Any pains?	Yes	No		
Where?	upper body	torso	lower body	
Specific Injury				
How much liquid intake?				
Comments				

Table C4: Breakdown of costs for 2006 season.

		AVERAGE	BEST	REALISTIC VALUES
OUTPUT	Tons/hour	3.05	4.59	3.5
	Tons/day	18.3	27.54	21
	Cutting days	190	190	190
	Tons cut per season	3477	5232.6	3990
LABOUR	Labour unit cost/day	40	40	50
	Number of labour units used	4	4	4
	Total labour cost per day	160	160	200
BLADES	Blade Duration per edge (min)	80	125	100
	Number of usable edges	4	4	4
	Blade life (hrs)	5.33	8.33	6.67
	Tonnes/blade	16.27	38.25	23.33
	Duration of plate (hrs)	10.83	16.67	16.67
	Cost for the plate	25	25	25
	Tonnes/plate	33.04	76.50	58.33
	Cost for 1 blade (R)	6	6	6
	Cutting sides	4	4	4
	Cost per Set	24	24	24
CAPITAL COSTS	Number of machines per team	3	3	3
	Capital outlay per machine (R)	8250	8250	8250
	Total capital outlay (R)	24750	24750	24750
	Dep (1st year)	4125	4125	4125
	Dep (2nd year)	1237.5	1237.5	1237.5
	Dep (3rd year)	247.5	247.5	247.5
	Average yearly depretiation	1870	1870	1870
OTHER COSTS	Fuel (l/hr)	1.6	1.6	1.6
	Cost per litre	5.5	5.5	5.5
	Maintenance Costs/year	5000	5000	3000
COST PER TONNE	Labour	8.74	5.81	9.52
	Blades	2.23	0.95	1.46
	Capital	0.54	0.36	0.47
	Fuel	2.89	1.92	2.51
	Maintenance	1.44	0.96	0.75
	TOTAL	15.84	9.99	14.72

C1. DEVELOPMENT OF THE SUGARCANE TOPPER

The system would perform quicker and more efficiently if a topper could be designed. This would stop the double handling of the cane and decrease the number of laborers needed. It was suggested that a pre-topper would work best and allow for the cane to be topped before it is cut. This would allow for more accurate topping and an even distribution of the tops over the whole field not in lines as seen in Figure C1.1.

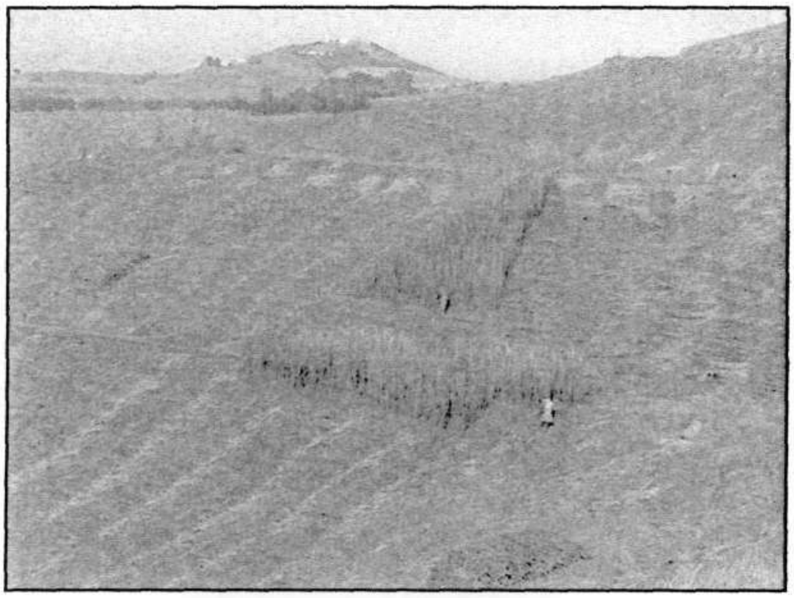


Figure C1.1 Tops lying in rows through the field and not evenly distributed throughout the field as a mulch layer.

C1.1 Aims

The aims were to develop a machine that tops the sugarcane in-field before cutting. This allows for more accurate topping and stops the double handling of the cane. It required being fast and efficient offering a clean cut at the correct height at the natural breaking point and distributing the tops evenly throughout the field. The natural breaking point is found at the top node of the cane.

C1.2 Design

It was decided to adapt current machines that do similar tasks like pruning. STIHL have a complete range used for pruning hedges. There are two dominant methods: either using reciprocating blades or a chainsaw.

C1.2.1 Reciprocating blades

This is attached to a chainsaw or a brushcutter head. The head is a standard 40 mm head with serrated reciprocating teeth as seen in Figure C1.2. The teeth are covered by a guard and is able to cut through twigs and branches up to 15mm thick. This is more than adequate to cut the tops of sugarcane and was decided to be tested.

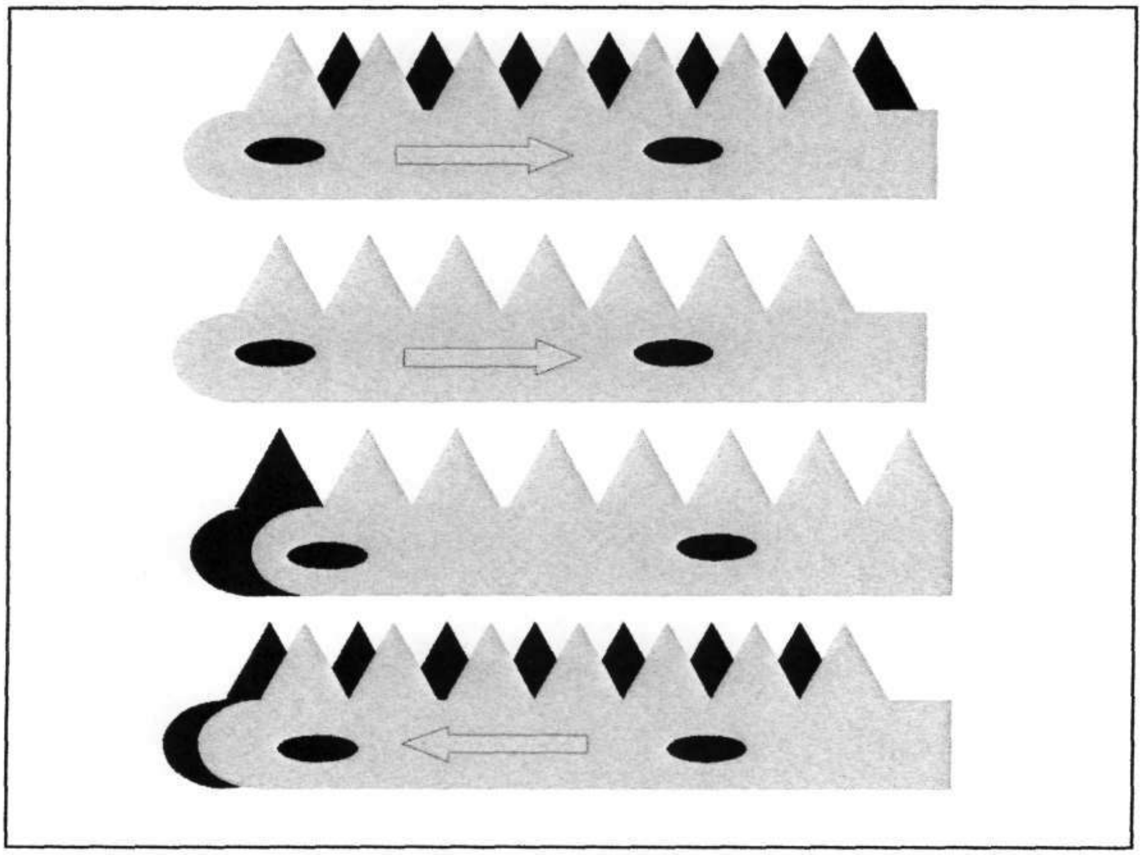


Figure C1.2 Reciprocating blades used for hedge trimming to top cane.

C1.2.2 Chainsaw head

The chain saw head required more adaptations and required the chain to be changed to allow maximum cutting. The gauging tooth was ground down to offer more bite so that the cane would not be pushed to one side (Figure C1.3). Unlike hard wood, sugarcane is soft therefore doesn't require to be cut gradually.

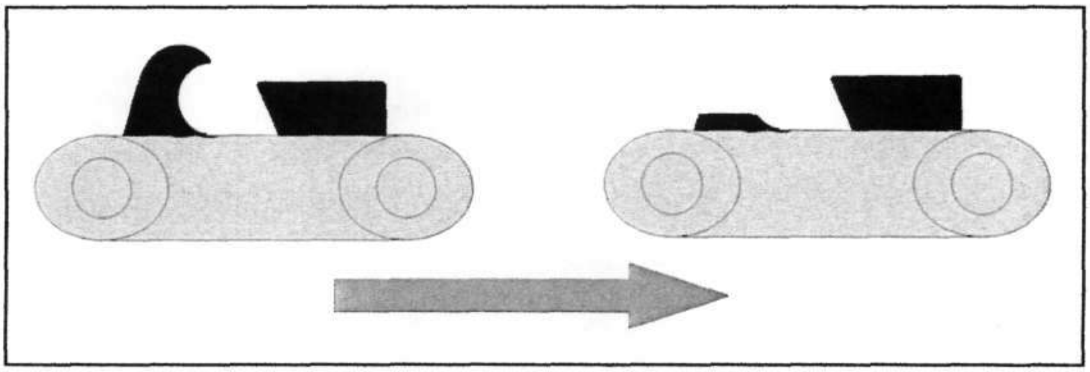


Figure C1.3 Exploded view of one chain link where the gauging tooth has been ground down to allow for maximum bite.

The cane would still be pushed aside not allowing it to be cut. A guard or tooth guide was designed and cut from 4 mm aluminium. This was bolted onto the head of the chainsaw seen in Figure C1.4 and the gap was between the teeth was originally 50 mm but testing showed that it required to be larger. The final design used was a comb with 20 mm teeth at 85 mm spaces between the teeth. The whole machine can be seen in C1.5.

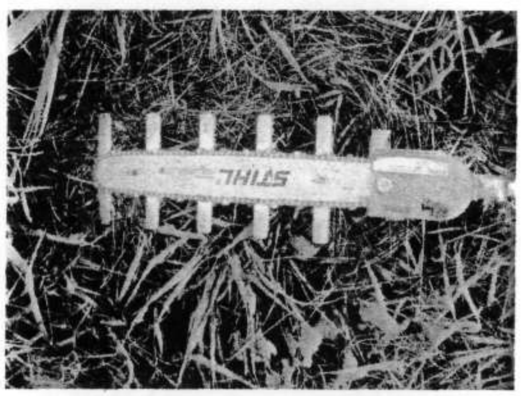


Figure C1.4 Aluminum comb chain saw cover that prevented the tops pushing to one side.

Figure C1.5 The hedge trimmer adapted with an angled chainsaw head to cut the tops.

C1.3 Results

Both designs were tested on Esperanza farm, Umzinto in 2005 and 2006 and it was determined that the reciprocating blades of a hedge trimmer did not cut the tops due to the tops being soft and pushed to one side. The chainsaw head had more favorable results. The method of cutting with the chainsaw head can be seen in Figure C1.5 and cuts the tops effectively and quickly shown in Figure C1.6.

Figure C1.5 Topping sugarcane using the adapted hedge trimmer with a chainsaw head.

Figure C1.6 Cut tops at the correct height with no damage with the adapted hedge trimmer and chainsaw head.

Problems with the system were that the tops did not fall to the ground but got caught in the stool and the cane (Figure C1.7). This results in the tops being loaded into the stack that decreases the purity and was not accepted by the mill.

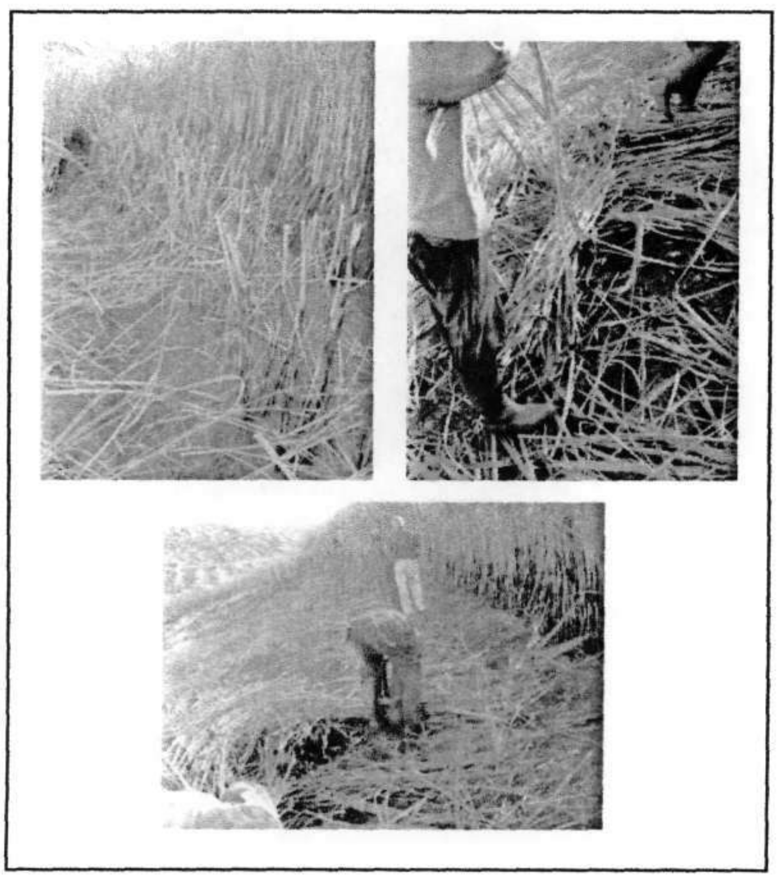


Figure C1.7 Cane that had been topped with the adapted hedge trimmer with the chainsaw head showing the tops becoming lodged in the cane and getting loaded into the stack.

C1.4 Conclusion and Recommendations

As a whole, the design failed and was not suitable for topping cane. The head with the ground down gauging tooth cut the tops effectively but once the tops are cut they are not placed in an order that allows for subsequent stacking of the cane without adding large amounts of tops.

Further recommendations are that an implement needs to be designed that pushes or blows the tops away from the cane row and drops them into the inter-row. This will stop the double handling of the cane and drop the costs of the system considerably.

APPENDIX D

Table D1: Energy Expenditure for manual topping of sugarcane.

	MEANS							
NAMES	WHR	pVO2	VO2 (l/min)	EE (KJ/min)	KJ/hr	KJ/shift	TONS	KJ/TONS
M1	124.79	25.17	1.49	29.90	1794.21	2386.31	3.10	769.78
M2	135.43	24.46	1.40	28.22	1693.25	2539.88	2.80	907.10
M3	112.90	34.93	2.07	41.57	2494.17	1995.33	6.40	311.77
M4	98.33	6.65	0.36	7.17	430.02	401.21	4.60	87.22
M5	132.81	13.93	0.87	17.39	1043.27	1210.20	7.00	172.89
M6	104.22	22.50	1.33	26.78	1606.66	2035.64	5.10	399.14
M7	112.66	14.74	0.89	17.86	1071.80	1071.80	3.10	345.74
M8	129.13	20.55	1.19	24.00	1439.82	1655.80	6.30	262.83
M9	107.35	19.26	1.38	27.75	1665.07	1665.07	2.80	594.67
M10	137.18	21.94	1.57	31.61	1896.81	2200.30	2.80	785.82
Average	**119**	**20**	**1**	**25**	**1514**	**1716**	**4.4**	**464**
Max	**137**	**35**	**2**	**42**	**2494**	**2540**	**7.0**	**907**
Min	**98**	**7**	**0**	**7**	**430**	**401**	**2.8**	**87**
Std Dev	**14**	**8**	**0**	**9**	**562**	**662**	**1.7**	**283**

Table D2: Results of energy expenditure for stacking sugarcane.

	MEANS							
Names	WHR	pVO2	VO2 (l/min)	EE (KJ/min)	KJ/hr	KJ/shift	TONS	KJ/TON
M1	123.76	24.71	1.46	29.35	1761.21	2342.41	3.10	755.62
M2	141.16	26.91	1.54	31.05	1863.14	1863.14	2.80	665.41
M3	120.06	39.29	2.33	46.75	2804.84	9115.75	6.40	1424.34
M4	110.60	10.21	0.55	11.00	660.13	1771.12	4.60	385.03
M5	145.12	17.79	1.10	22.20	1332.12	3596.72	7.00	513.82
M6	110.57	24.92	1.47	29.65	1778.81	3260.57	5.10	639.33
M7	123.23	19.10	1.15	23.16	1389.31	2848.08	3.10	918.73
M8	147.07	26.97	1.57	31.50	1889.72	4686.50	6.30	743.89
M9	104.28	18.49	1.33	26.64	1598.60	3996.50	2.80	1427.32
M10	142.88	23.93	1.72	34.49	2069.51	4366.67	2.80	1559.53
Average	**127**	**23**	**1**	**29**	**1715**	**3785**	**4.4**	**903**
Max	**147**	**39**	**2**	**47**	**2805**	**9116**	**7.0**	**1560**
Min	**104**	**10**	**1**	**11**	**660**	**1771**	**2.8**	**385**
Std Dev	**16**	**8**	**0**	**9**	**553**	**2125**	**1.7**	**418**

Ingesta:

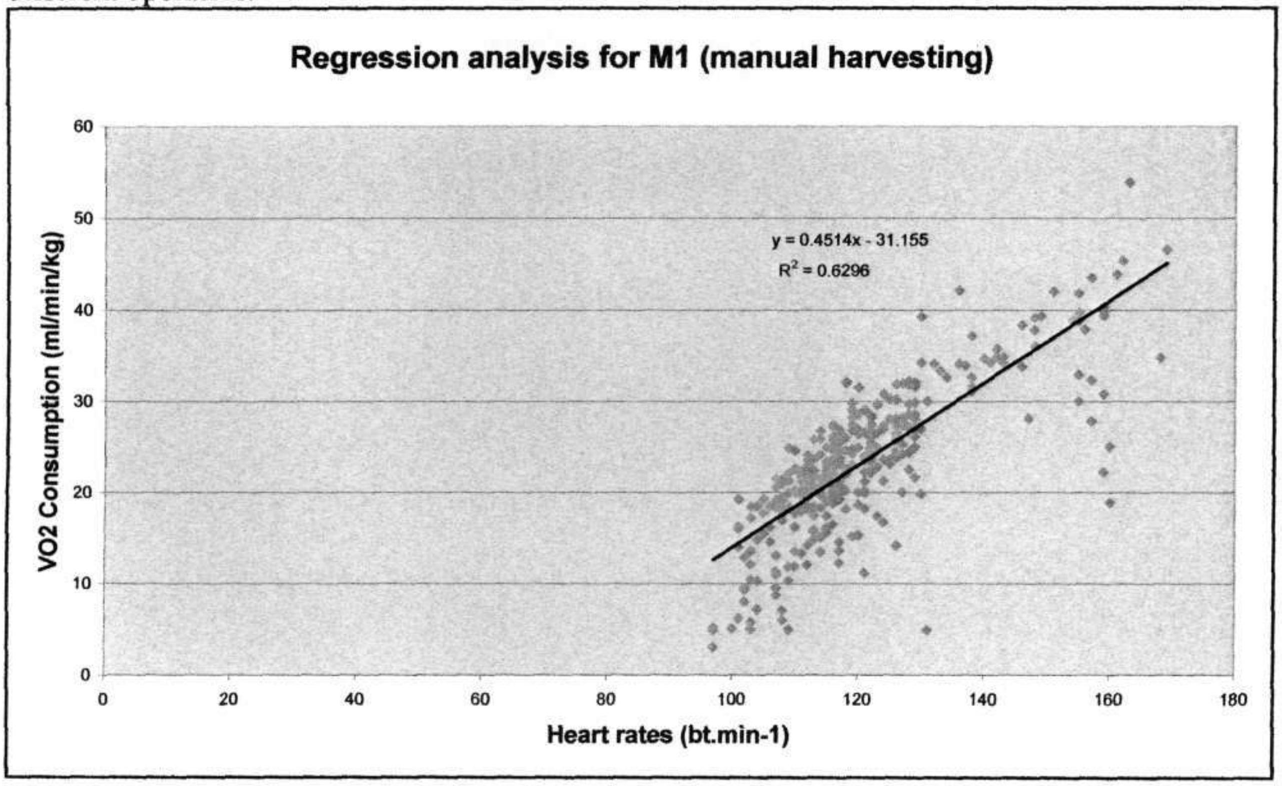
Manual workers

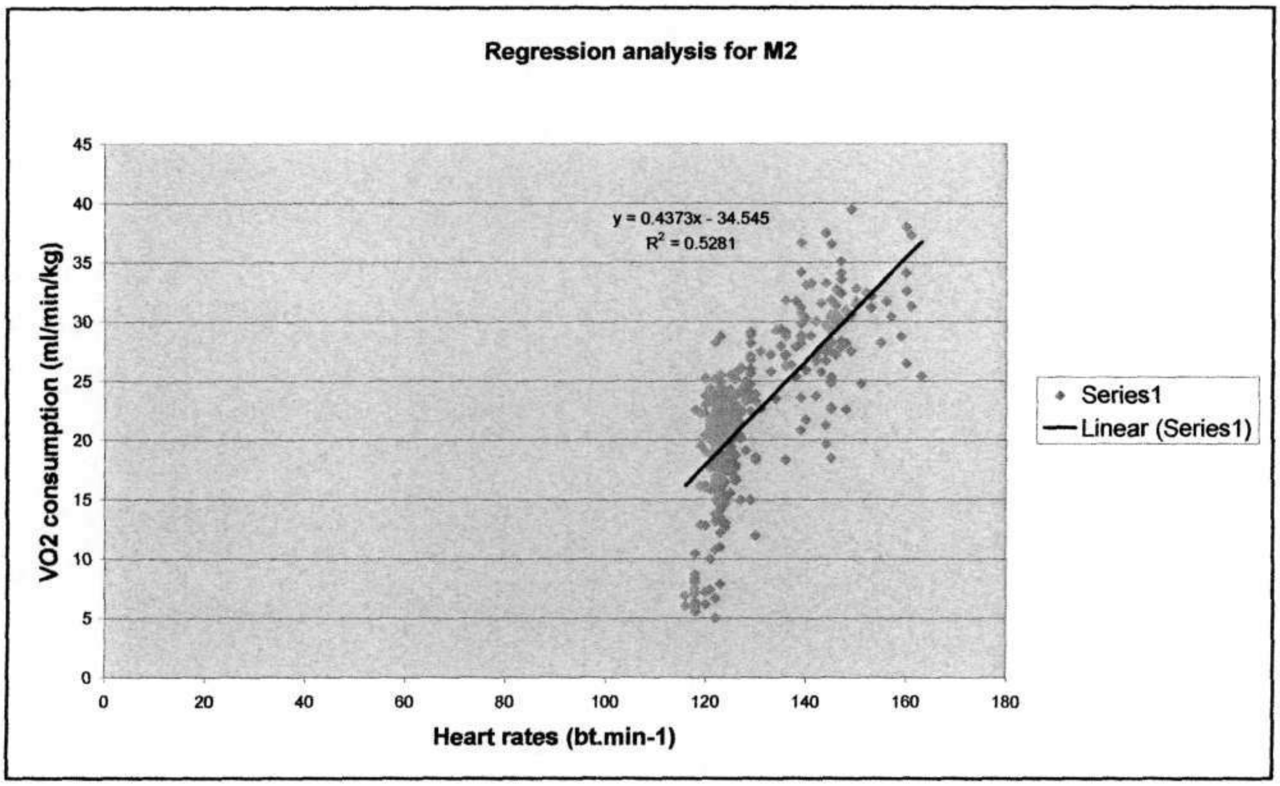
M8– 3.5L
M7– 3.5L
M5– 5L
M9– 5L
M10 – 500ml water
M6– ate lots of sugar cane, approx. 500ml mageau
M3– 1L (1 loo break)
M1– 500ml water,
M2– 750ml mageau
M4– 2L

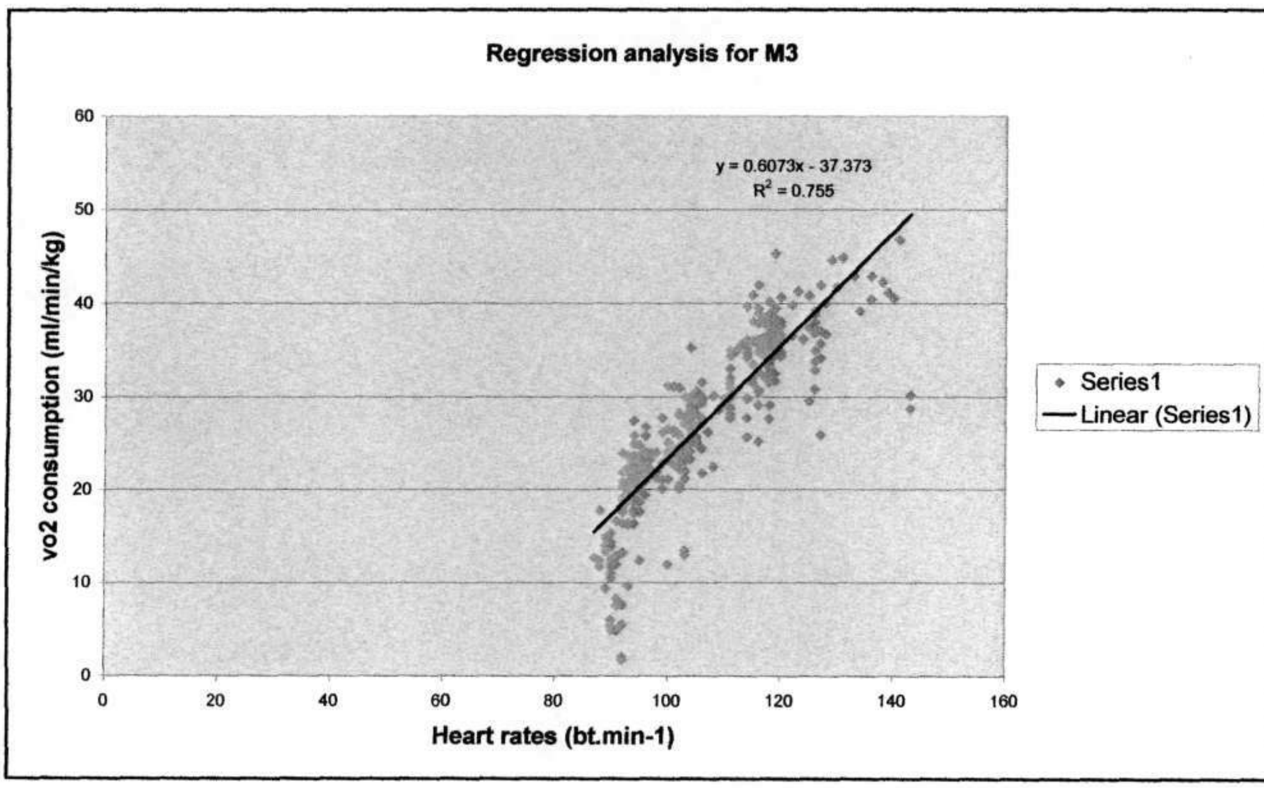
Machine operators:

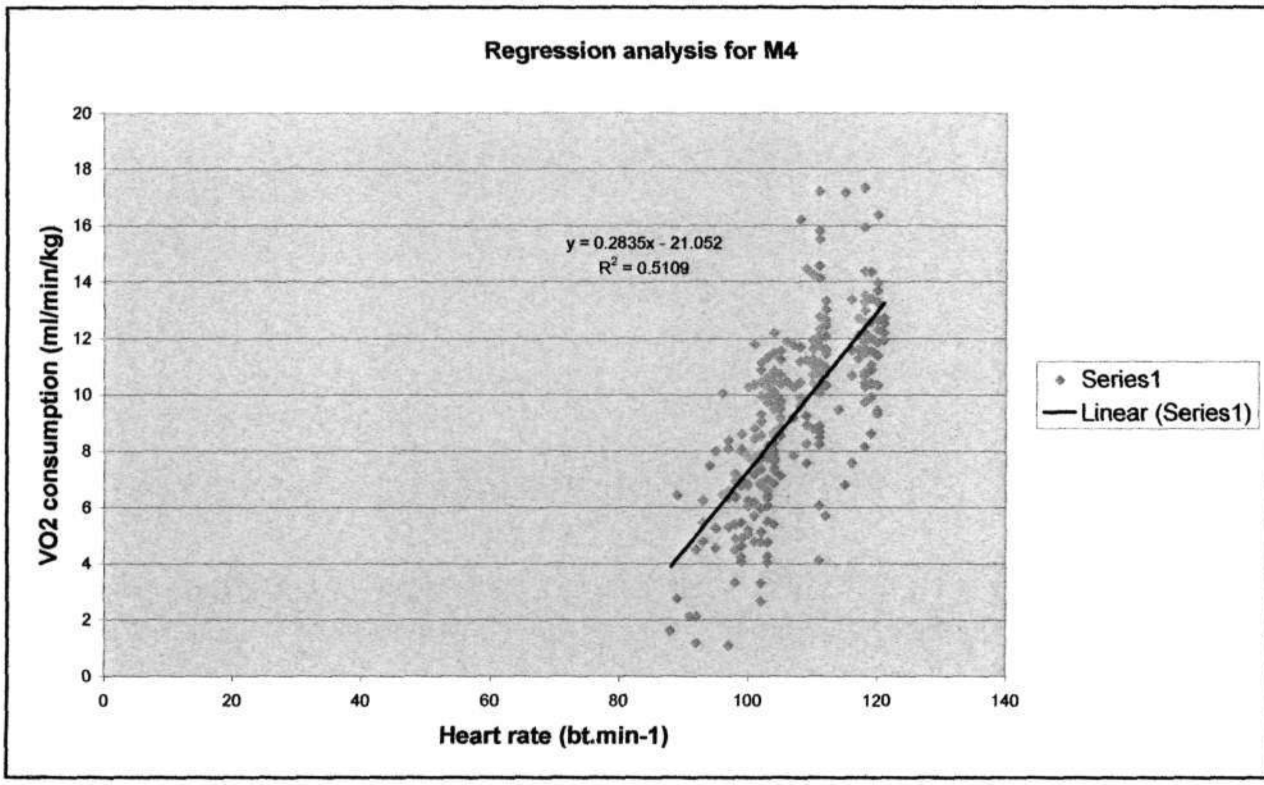
M2 – 600ml water
M1 – 400ml water
- bowl of rice, potatoes (2), carrots (1), chicken (breast)

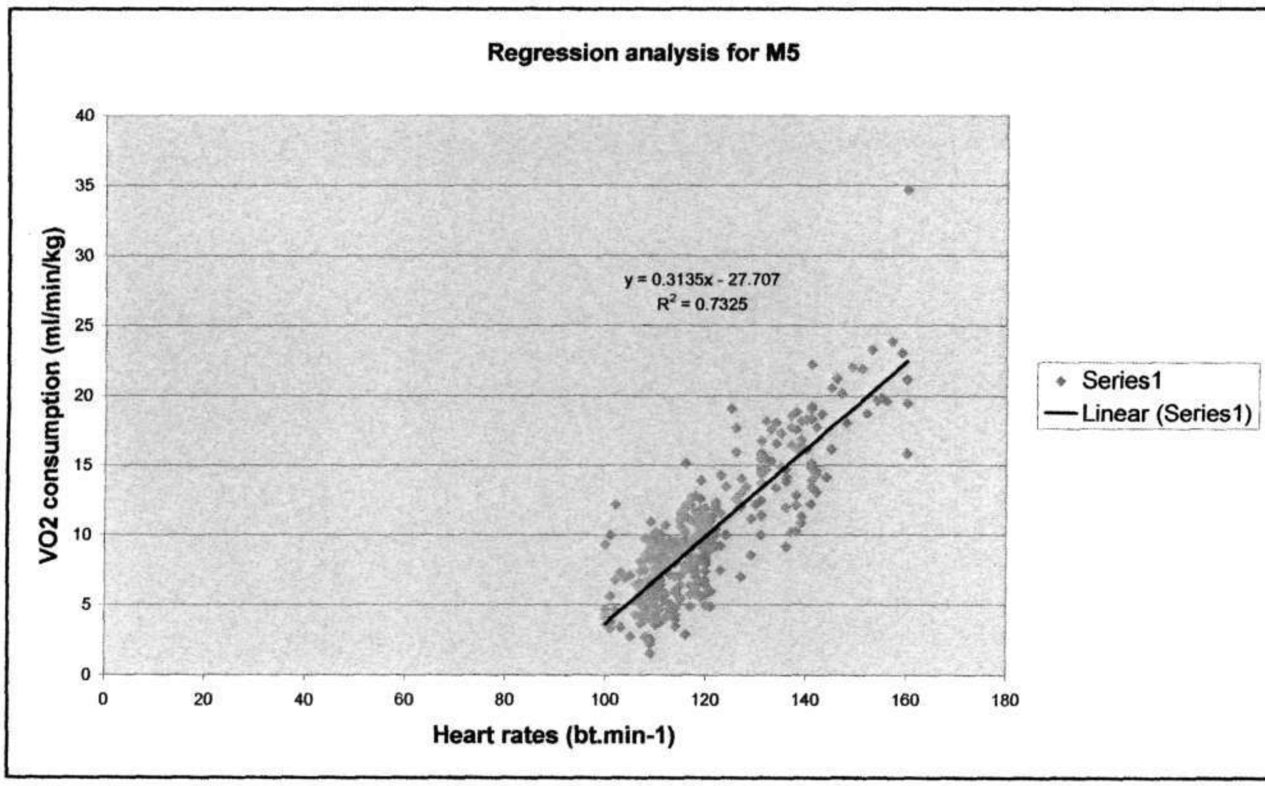
The following Figures D1- D11 shows the regression analysis for the heart rate too VO_2 for the different operators:

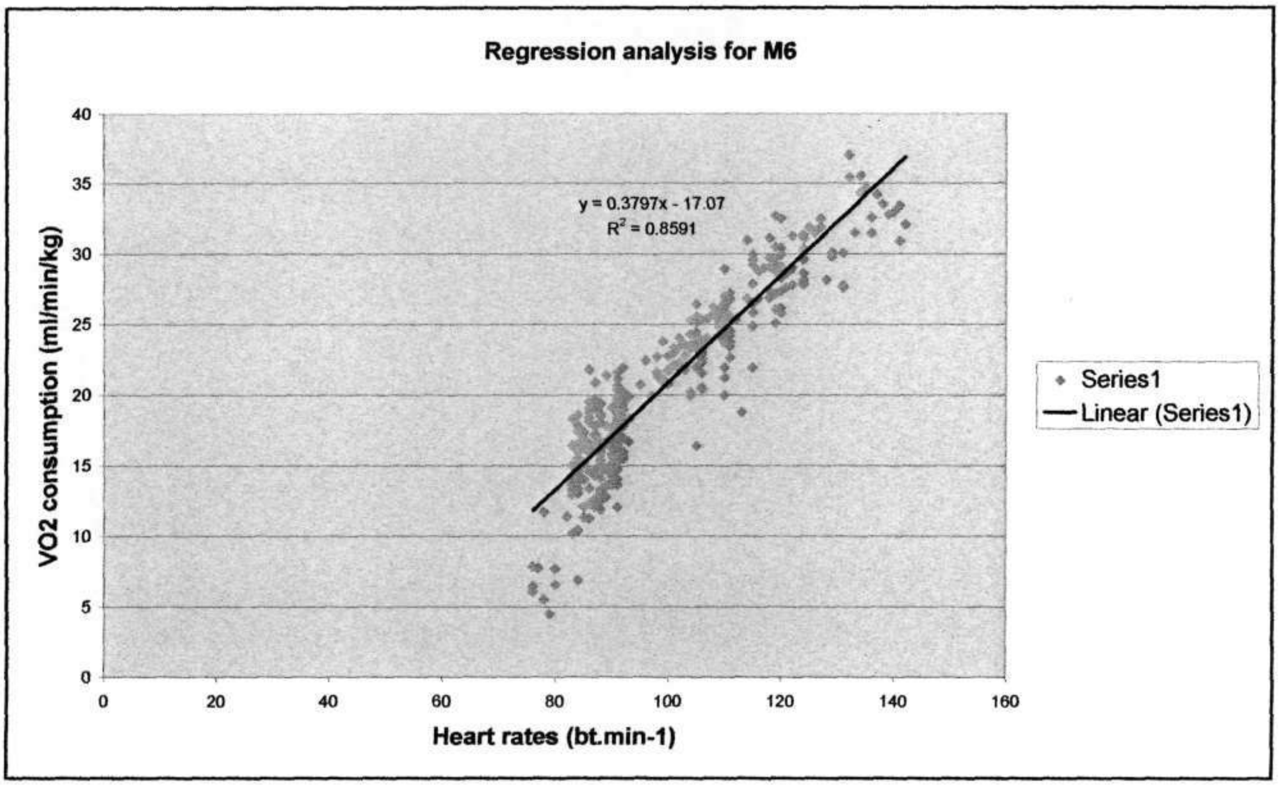


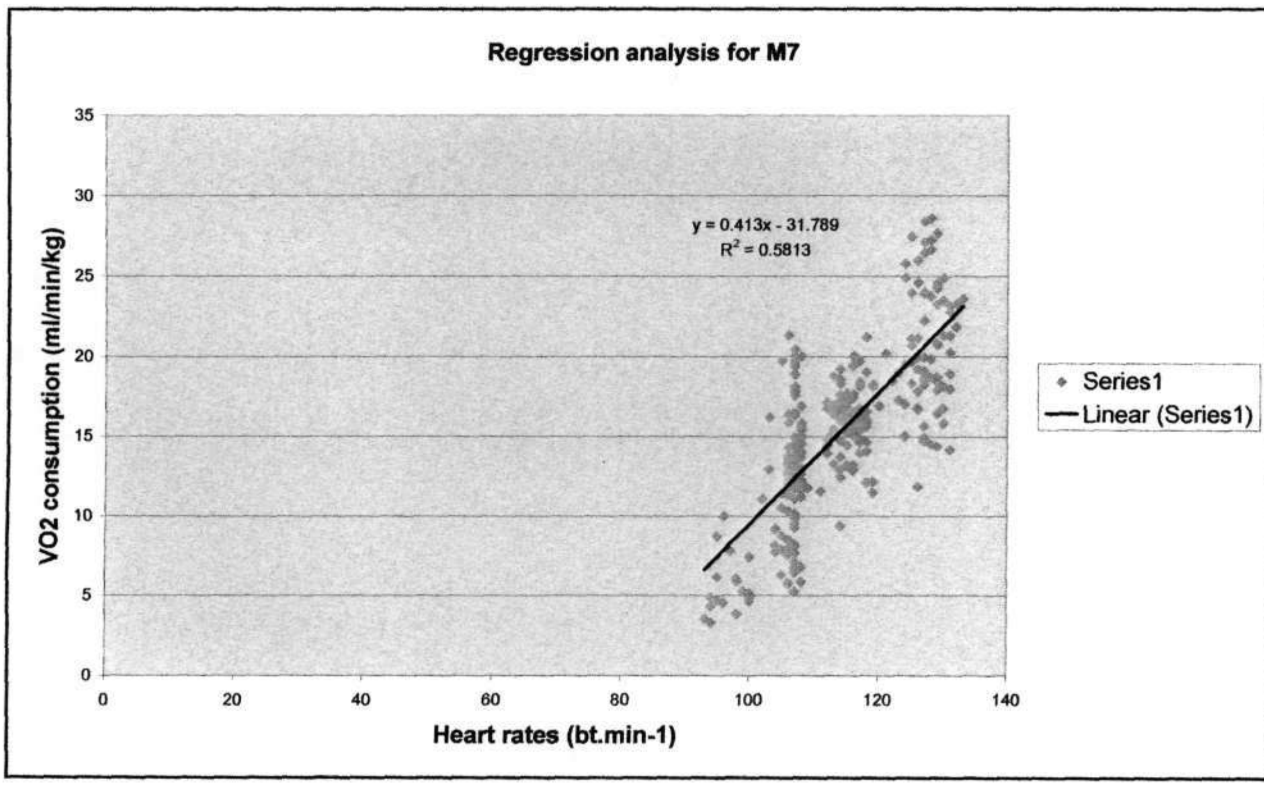

Regression analysis for M2
y = 0.4373x - 34.545
R² = 0.5281
VO2 consumption (ml/min/kg)
Heart rates (bt.min-1)
Series1
Linear (Series1)
0
5
10
15
20
25
30
35
40
45
0
20
40
60
80
100
120
140
160
180

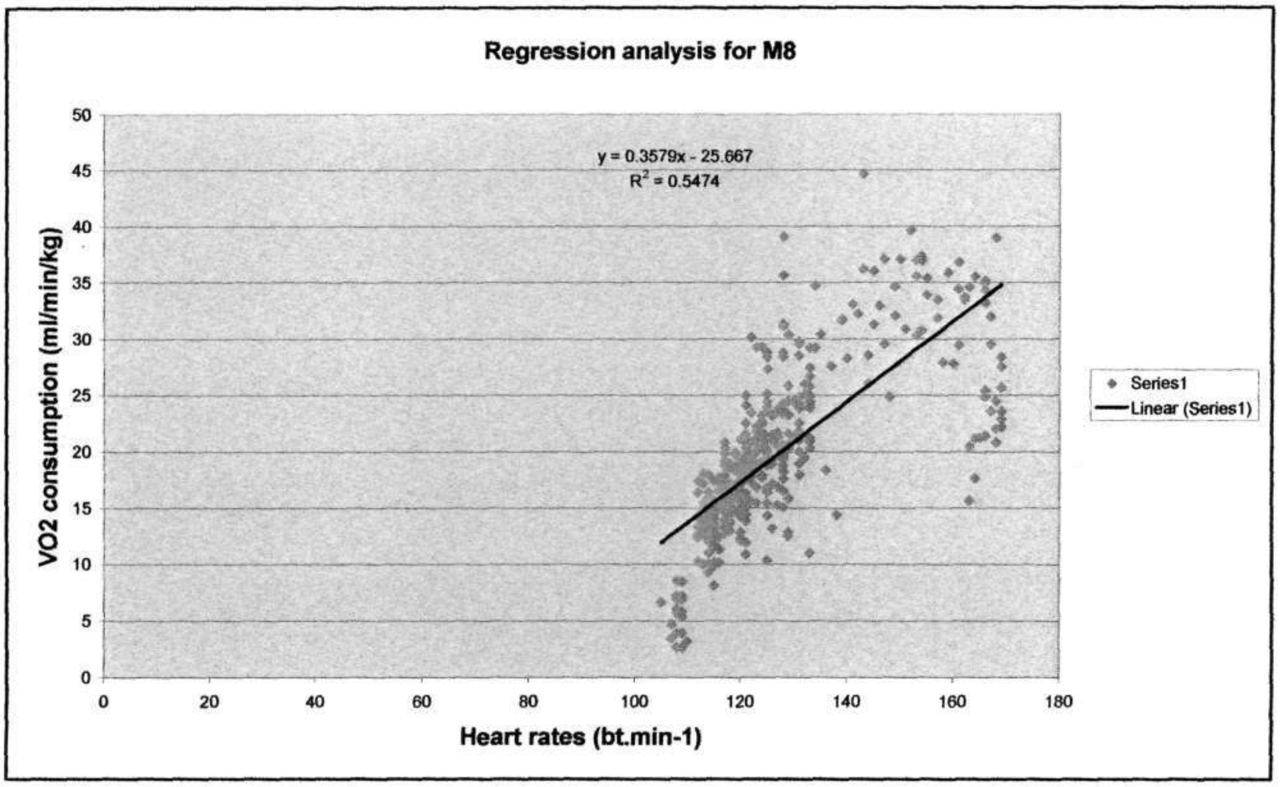

Regression analysis for M3
y = 0.6073x - 37.373
R² = 0.755
vo2 consumption (ml/min/kg)
Heart rates (bt.min-1)
Series1
Linear (Series1)
0
10
20
30
40
50
60
0
20
40
60
80
100
120
140
160


Regression analysis for M4
y = 0.2835x - 21.052
R² = 0.5109
VO2 consumption (ml/min/kg)
Heart rate (bt.min-1)
Series1
Linear (Series1)
0
2
4
6
8
10
12
14
16
18
20
0
20
40
60
80
100
120
140

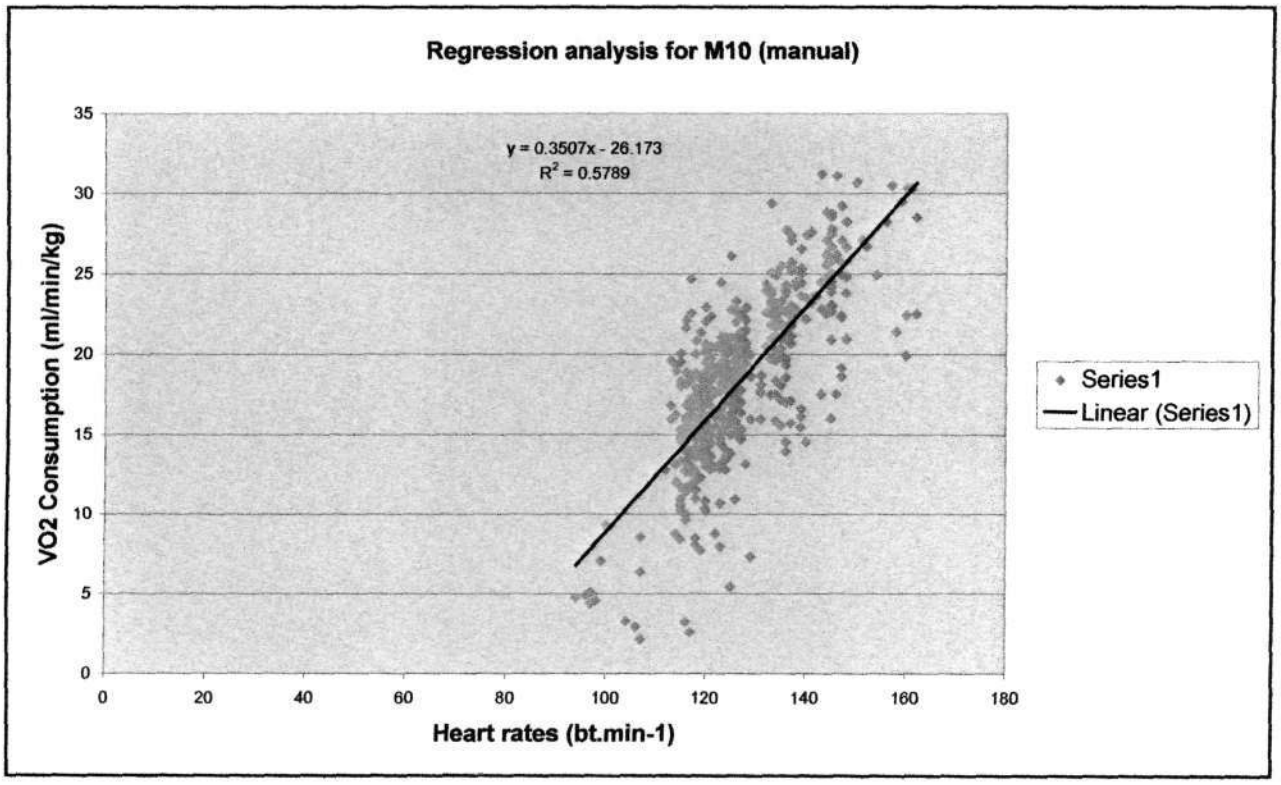

Regression analysis for M5
y = 0.3135x - 27.707
R² = 0.7325
VO2 consumption (ml/min/kg)
Heart rates (bt.min-1)
Series1
Linear (Series1)
0
5
10
15
20
25
30
35
40
0
20
40
60
80
100
120
140
160
180


Regression analysis for M6
y = 0.3797x - 17.07
R² = 0.8591
VO2 consumption (ml/min/kg)
Heart rates (bt.min-1)
Series1
Linear (Series1)
0
5
10
15
20
25
30
35
40
0
20
40
60
80
100
120
140
160

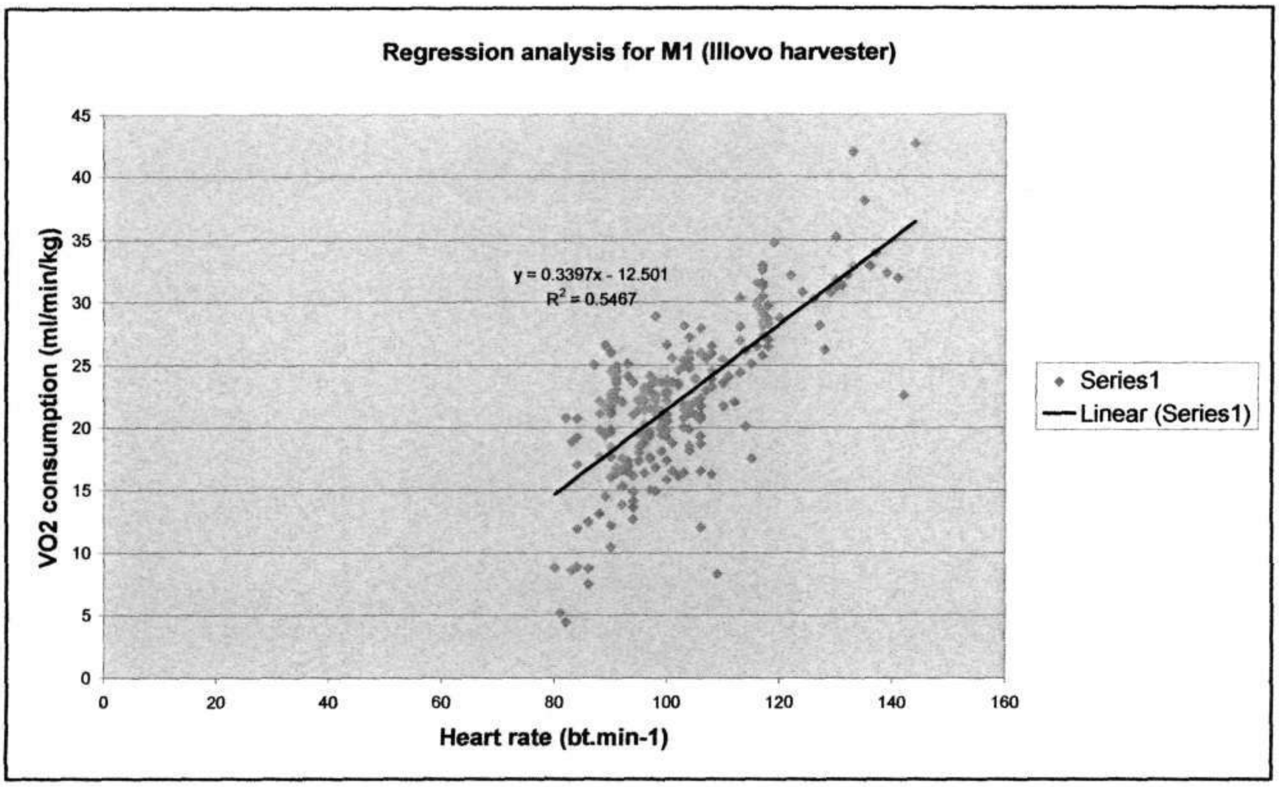

Regression analysis for M7
y = 0.413x - 31.789
R² = 0.5813
VO2 consumption (ml/min/kg)
Heart rates (bt.min-1)
Series1
Linear (Series1)
0
5
10
15
20
25
30
35
0
20
40
60
80
100
120
140



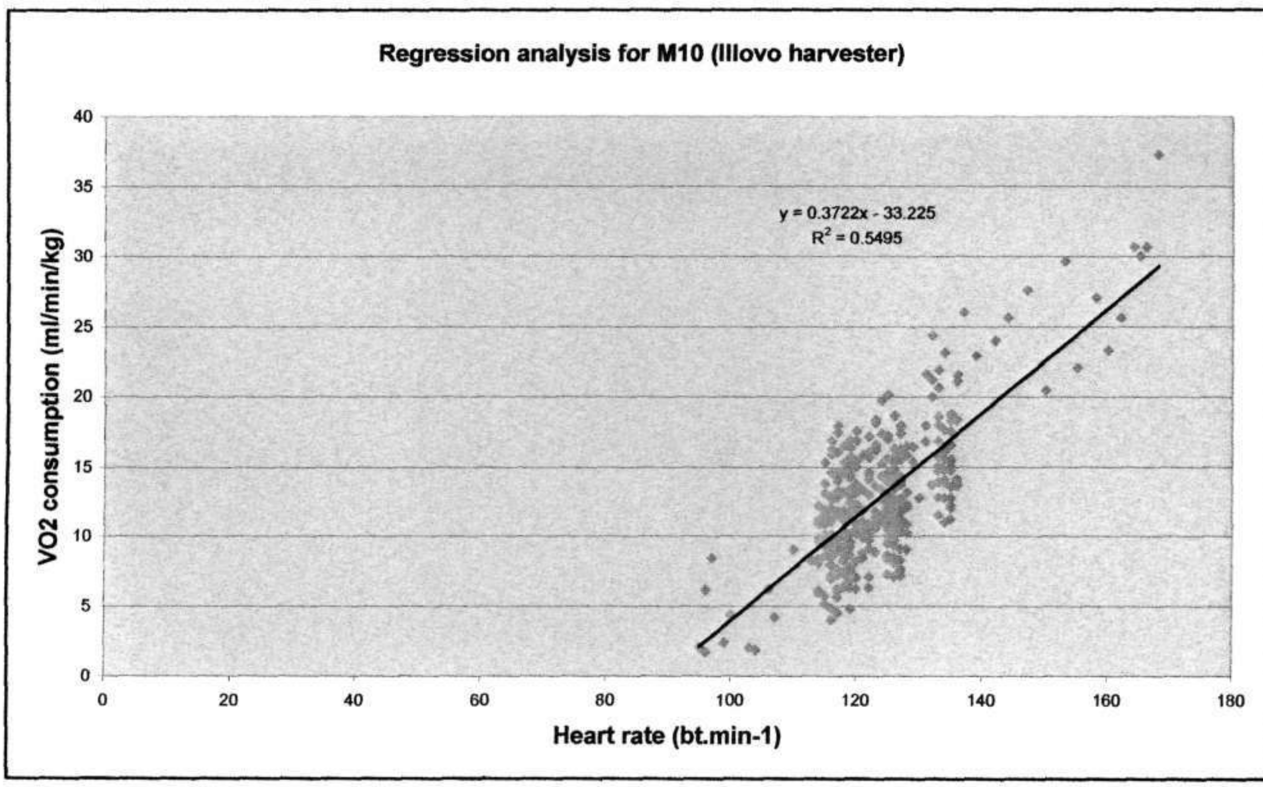
Regression analysis for M8
y = 0.3579x - 25.667
R² = 0.5474
VO2 consumption (ml/min/kg)
Heart rates (bt.min-1)
Series1
Linear (Series1)



Regression analysis for M10 (manual)
y = 0.3507x - 26.173
R² = 0.5789
VO2 Consumption (ml/min/kg)
Heart rates (bt.min-1)
Series1
Linear (Series1)



Regression analysis for M1 (Illovo harvester)
y = 0.3397x - 12.501
R² = 0.5467
VO2 consumption (ml/min/kg)
Heart rate (bt.min-1)
Series1
Linear (Series1)



Regression analysis for M10 (Illovo harvester)
y = 0.3722x - 33.225
R² = 0.5495
VO2 consumption (ml/min/kg)
Heart rate (bt.min-1)

Table D3: Results from the LMM for the different movements.

Movement		Illovo Cutter	Manual
maximum left bend	(degrees)	4.455	10.1
maximum right bend	(degrees)	4.295	17.63
maximum lateral range	(degrees)	6.61	26.83
maximum extension	(degrees)	4.155	7.14
maximum flexion	(degrees)	3.55	28.57
maximum sagittal range	(degrees)	7.71	23.12
maximum left twist	(degrees)	1.65	11.11
maximum right twist	(degrees)	10.015	10.82
maximum twisting angle	(degrees)	11.175	21.93
average lateral velocity	(degrees/sec)	2.82	17.23
maximum lateral velocity	(degrees/sec)	13.4	63.18
average sagittal velocity	(degrees/sec)	3.135	10.99
maximum sagittal velocity	(degrees/sec)	19.845	46.8
average twisting velocity	(degrees/sec)	4.095	18.78
maximum twisting velocity	(degrees/sec)	28.835	69.75
maximum lateral acceleration	(degrees/sec2)	81.94	490.52
maximum sagittal acceleration	(degrees/sec2)	134.93	364.34
maximum twist acceleration	(degrees/sec2)	192.955	545.49

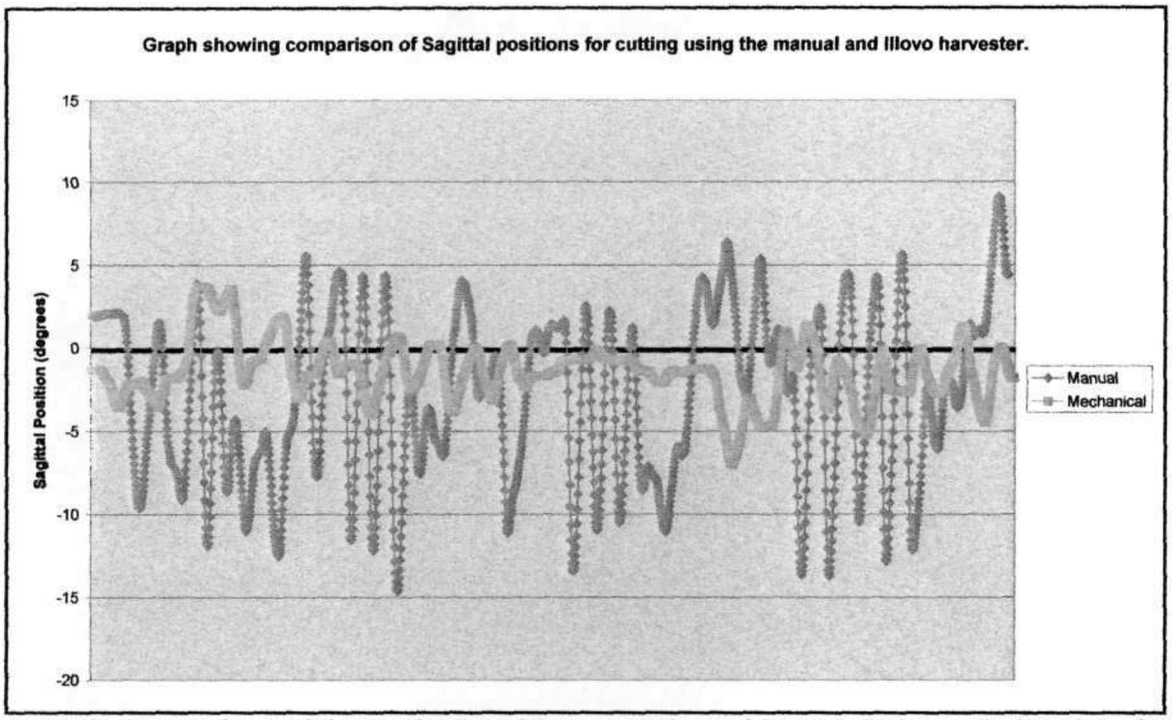


Figure D12: Comparison of the Sagittal positions experienced by M1 during a similar time frame.

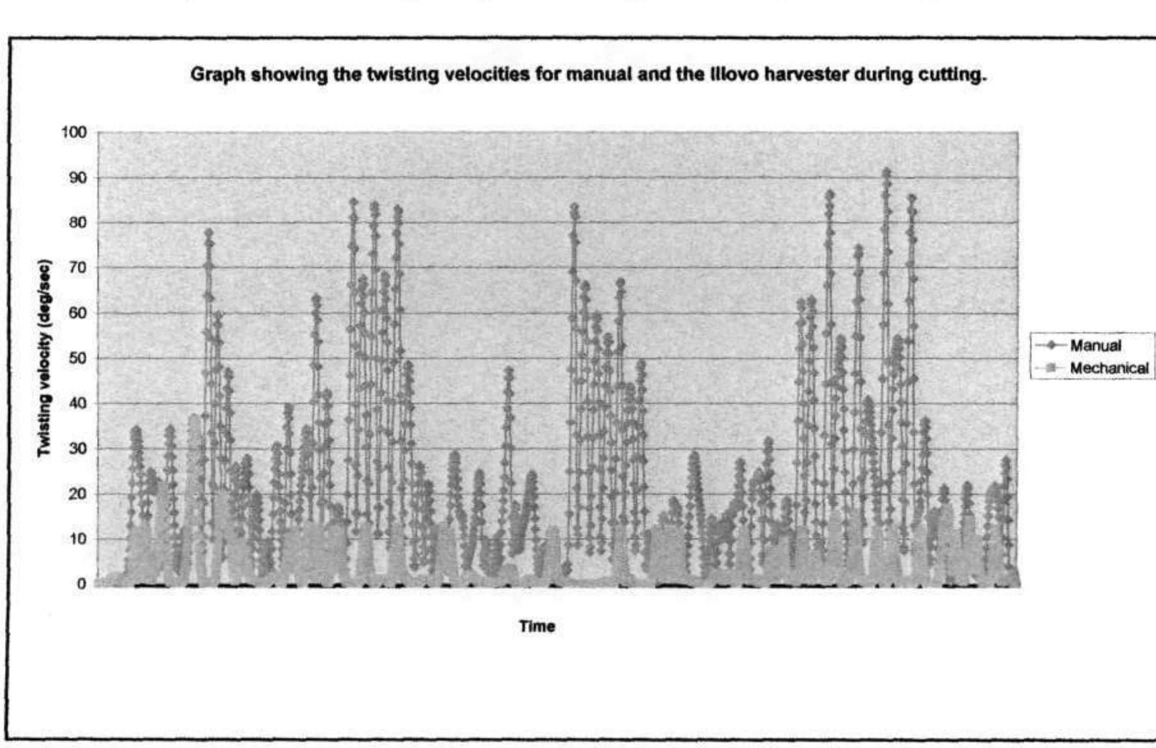


Figure D13: Comparison of the Twisting velocities experienced by M1 during a similar time frame.

APPENDIX E

E1. CHANGING MANAGEMENT AND SYSTEMS

Once the current system is understood and a new system has been developed and it has been determined how to increase the productivity, the work has only just begun (McCown, 2002). McCown (2002) also stated that farmers are very reluctant to change but according to Kotter and Cohen (2002) said that the human race as a whole is reluctant to accept change.

The question often asked is why change is necessary? The answer is that it is essential to remain competitive in a changing and growing market (Wagner, 1999). If change is not carried out a business or organization will decrease their profitability. Innovation is an essential element to maintaining and enhancing profitability and international competitiveness. What always follows innovation is a change that starts with management and which cascades down to different levels (Muchow *et al.*, 2000).

Some of the biggest product failures are not because the product was not good, but rather the inability to change people's ideas and perception caused the failure (Kotter and Cohen, 2002). By implementing the right type of change a smooth transition is possible (Bourne and Bourne, 2002).

E1.1 Types of Change

There are many types of change but common dimensions to change are outlined by Bourne and Bourne (2002) as:

- incremental change or radical change,
- continuous improvements or step change, and
- participative or directed change.

These dimensions are linked since incremental change is through the process of continual improvements and radical change is related to a large step that is very visible. Table E1.1 outlines some advantages and disadvantages of continuous change and step change. The situation determines which change system to use and how desperately the changes are required. Whichever change system is implemented, it is vital to remain focused and not deviate from the end vision as it is these deviations that cause change to stop happening (Thiry, 2004).

Table E1.1 Advantages and disadvantages of continuous improvement and step change (after Bourne and Bourne, 2002).

	Advantages	**Disadvantages**
Continuous Improvements	Many small steps. Makes change habitual. Less disruptive. Lower risk. Creates cumulative gains.	Slow. May create tunnel vision and missed opportunities.
Step Change	Stimulates radical thinking. Potential quick gains.	Greater risk. Disrupts performance during change.

E1.2 Why Does Change Fail

The following are 8 reasons of why change fails that were presented by Kotter and Cohen (2002) and by addressing each issue, change may be implemented successfully:

- Not creating enough urgency at the start of the change and, if the reason for changing are not clear, people will not change.
- Not using the right people to implement the change: The highest ranking people in the industry need to show that this change is important.
- Underestimating the power of vision.
- Not enough communication taking place, both verbally and by actions taken. Actions taken need to be consistent with verbal communication.
- Permitting obstacles to remain which blocks progress. People know the obstacles and by not removing the obstacles the perception is created that the need for change is not serious.

- By not creating short term goals and showing successes so that people involved are aware of what is being achieved. Projects lose initial momentum and by creating success in short term goals creates momentum.
- By declaring victory too soon since the change management team wants to announce they succeeded as soon as possible and this is when the momentum for change slips and people revert to the old systems.
- Neglecting to enforce the change and making it stick in the organization.

By avoiding these common errors, change can be implemented smoothly. In implementing change the main focus is people and the interactions at the various levels of management. It is not possible to implement a set of rules to make change succeed but by consistently monitoring it is possible to succeed (Bourne and Bourne, 2002).

E1.3 Stages in the Change Process

The three main stages of change that have been identified are unfreezing, moving and refreezing. Although many other more complex models have been developed, these stages are still the most practical (Lewin, 1951 cited by Weick and Quinn, 1999).

E1.3.1 Unfreezing

This involves the company or organization to prepare for a change. The need for change must be recognized and alternatives or solutions need to be developed. It also involves changing people's mindsets and personal ideas. This is a vital step and a change strategy will fail without taking the correct steps in unfreezing (Bourne and Bourne, 2002). Bourne and Bourne (2002) presented the following steps to help with unfreezing:

- Identify the need for change early.
- Avoid the panic response from employees by using communication.

- Communicate as much as possible, preferably face to face, and answer just the necessary questions. These questions include what are the changes, why are they happening, what will the end result be and what it will mean for the employee?
- Create a burning platform with no return which means to not give any other option but to proceed with the agreed changes.

E1.3.2 Moving

This is often called 'the change roller-coaster' because of the up and down feelings of the labourers caused by the change program. It usually starts with not accepting the change and having a decrease in productivity. However, when the program starts to get accepted, the productivity increases and finally a happier, more secure organization are established (Bourne and Bourne, 2002).

There are a few ways that a manager can help to alleviate this resistance (Bourne and Bourne, 2002):

- Accept the resistance, the anger by employees and irrational responses and do not be surprised by it.
- Plan for the decrease in performance during the transition.
- Provide necessary support and information.
- Negotiate realistically and give in to areas that can be conceded but not those that affect the change.
- Encourage and help experimentation with the new working methods.
- Set clear targets and goals to give the sense of accomplishment and achievement to the worker.

There are three basic options in designing change. They are collaboration when a team is formed and work through a change program. Consultation is when an outside firm or individual presents a motion where it gets accepted or rejected. The final method is communication and occurs when people are told what is going to happen with little or no input at all. This last approach is becoming less possible since it usually creates a large resistance (Bourne and Bourne, 2002).

E1.3.3 Refreezing

This is the final stage and is the process where the idea gets anchored to ensure that the benefits of the change are not lost or to stop the company slipping back into its old habits and ways of operating. It is optimal to have a change where the benefits are so apparent that the company does not want to go back, but this is unlikely to occur. According to Bourne and Bourne (2002), the three ways to refreeze an organization are by anchoring the change in the organization's structure, by using a recognition and reward system or changing the organization's culture.

Anchoring the change in the organization's structure is very difficult but shows immediately where the problems and areas of focus should be. Changing an organization's structure often involves dismissing all the employees and moving the organization which is also difficult to implement but the most effective in keeping the changes. Anchoring using a recognition and reward system involves support systems that use incentives, rewards, recognition and analyses performances. It is necessary to ensure that the incentives and rewards are aligned with the change. The rewards need to be the greatest in the areas where change has occurred so as to focus the employee's attention in maintaining the new system. Anchoring through changing the organization's culture is the most difficult to achieve, but it is the most successful way of anchoring. This occurs when the employees of an organization are convinced that the new methods of operating are the best and only way. Aligning the structures and incentives is the first step and the change in culture comes down from senior management.

In refreezing the most important aspects is making sure that what is being said is clearly understood and is actually happening. When change has occurred it is important to make sure that it is present throughout the business and to make sure that senior management continues to act in a way that supports the change (Bourne and Bourne, 2002).

E1.4 Change Management Process

Although the three stages in change are fundamental and a good basis, it is often not in enough detail (Weick and Quinn, 1999). Kotter and Cohen (2002) and Thiry (2004) outlined some basic steps to implement change. This process is illustrated in Figure E1.1.

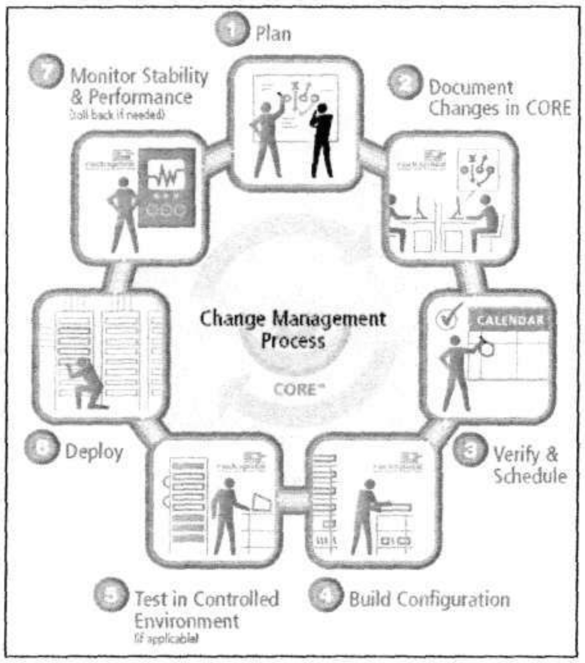


Figure E1.1 Steps in the change management process (Rackspace Managed Hosting, 2005).

The process always starts with designing and planning once the company knows what and where the problem areas are. This is followed by documentation to convince the organization and management that the implementation will work. This is followed by scheduling and planning a timeline so as to have definite short term goals. The initial testing is then done by building and testing in a controlled environment. If this is successful, the changes can be deployed and implemented in the entire organization. If the testing was not successful it is necessary to return back to step one and re-plan or design. Once the change has been implemented, a continual assessment needs to take place to ensure that the change is a success. If it is not successful and the benefits are not as significant as anticipated, the cycle must be started again.

E 1.5 Adapting the Change to be Sensitive to the Employee

Kotter and Cohen (2002) stated that organizations will continually have to implement change and the best way to overcome this is to follow a plan that has been clearly marked with distinctive short term goals. Urgency needs to be instilled and an effective change team assembled who all follow and have the same vision and who do not stop communicating, thus building trust and acceptance. Obstacles should not be allowed to stop the change from happening and thus to create a lasting solution.

These are all ways to ensure that change will happen but problem areas will not be identified without continual observation taking place. The change plan needs to be adapted and re-directed with continual clear thinking. There are a number of ways to achieve the intended outcome and the willingness to change and adapt the change process will make the transition happen faster and smoother.

The most important factor is human emotion and if the change is not sensitive to this, negative emotions will arise which include anger, mistrust, arrogance, pessimism, panic and anxiety. The emotions needed are faith, trust, optimism, enthusiasm and excitement. Once these are achieved, change will happen effectively and swiftly (Kotter and Cohen, 2002).

E1.6 References

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