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A review of opportunities to improve the design and performance of sugarcane harvesters

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A REVIEW OF OPPORTUNITIES TO IMPROVE THE PERFORMANCE OF SUGARCANE HARVESTERS
PROJECT FSA 001

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EXECUTIVE SUMMARY

The evolution of the sugarcane harvester in Australia has been a unique blend of the developments of farmer innovators, small manufacturers, and the research and development teams of larger corporations. The pioneering ‘chopped cane’ harvester was the Massey Ferguson 515, side mounted on a farm tractor. By 1975 around 98% of the crop was cut by ‘chopped cane’ harvesters. In 1979, Australia became the first sugar producing nation to convert entirely to mechanical sugarcane harvesting. Therefore, the Australian industry has the longest experience with mechanisation of any sugarcane industry.

The Australian type ‘chopped cane’ sugarcane harvester is a single row, over-the-row machine with a swinging elevator capable of delivering sugarcane to either side or to the rear of the harvester. The basic principles used in ‘chopped cane’ sugarcane harvesters have not changed significantly since they were first developed. The main changes are related to improved feeding and cleaning during green cane harvesting and increased capacity.

Mechanical harvesting of sugarcane has been a major success story for the Australian sugarcane industry. However, the Australian sugarcane industry has suffered a plateau in productivity and there is considerable evidence that mechanisation is a component.

By the late 1970’s, the advantages of harvesting green cane were beginning to be assessed by industry. Hence, early investigations into ‘chopped cane’ harvester performance were centred on green cane harvesting ability and loss comparisons with burnt cane harvesting. Against this background, the harvester manufacturing industry was developing the conceptual requirements for new machines.

Fundamental research on understanding the interactions between the crop and machine components commenced in the mid 1990’s along with evaluation of ongoing cane quality (EM/Dirt) and cane loss issues.

In recent times the industry has been striving to improve the efficiency and productivity of its sugarcane harvesting and transport practices. This has been through system modelling and aiming to achieve greater ownership of the magnitude of sugar losses and to encourage novel industry-led approaches to reduce harvesting losses.

The Sugar Research and Development Corporation (SRDC) has provided significant investment in harvester technology and harvesting operations aimed at developing and implementing innovative technology and best management practices that enhance revenue, and improve capital utilisation and environmental performance in sugarcane harvesting and transport.

This review is a response to the recognition by the SRDC that the Australian sugarcane industry needs an informed basis from which to make decisions as to appropriate investments in harvesting sector research. There is a renewed interest at a grower and regional level for improved harvester designs and harvesting practices. SRDC continues to receive requests from industry to support sugarcane harvester research and development.

This review looks at component research on the Australian type ‘chopped cane’ sugarcane harvester, harvesting performance and harvest and transport system analysis undertaken in
Australia and overseas and considers the benefits delivered. Opportunities to improve the design and performance and reduce the costs of sugarcane harvesting along with recommendations for further research, development and extension to facilitate productive and profitable adoption are identified.

It is concluded that ‘chopped cane’ harvester and harvesting performance research has delivered significant direct and indirect benefits to the Australian sugar industry and a number of key examples are highlighted to demonstrate these benefits.

Manufacturers perceive the worldwide market for ‘chopped cane’ sugarcane harvesters to be small, relative to the market for 'mainstream products'. The Australian sugarcane harvester market is very small in comparison with other countries such as Brazil. The Brazilian market now approaches 1000 machines per year. There will be about 9 machines sold into Australia in 2009. However, manufacturers see Australia as the world leader in machine performance research. It is unlikely that large sums will be invested in new technology and in particular for Australian requirements. Therefore it is imperative for industry profitability that there is a program of industry support aimed at improved machine performance and harvesting best practice (HBP).

There are two major issues facing the Australian sugar industry that may lead to significant changes in harvester design and harvesting systems. These are new farming systems and the cost of harvesting. The industry must have a clear vision of the purpose of the machine and design considerations to allow targeted investment. The key tasks in RDE for these issues are as follows:

a) Industry must move towards a controlled traffic system and therefore there is a requirement to develop harvesting strategies and solutions for row spacing configurations.

b) Assessment of the utility for wide–swath harvesting to contain harvesting costs, the most appropriate machine design and impact on the value chain. The Industry needs to identify opportunities to achieve wider-swath harvesting under a controlled-traffic system i.e. limitations with Corradini Two-in-One® type systems.

c) Evaluation of the issues with current machines associated with increased pour rates.

2. A fundamental understanding of the machine-crop interactions in particular the principles and concepts associated with gathering, feeding, basecutting, billeting and cleaning of sugarcane has been gained through component research. This has raised awareness of the issues involved during these processes and been the catalyst for novel industry-led approaches to improve the performance of machines. It has also led to world-leading technological innovation in mechanical harvesting from which the industry has directly benefited, which would not have occurred without the assistance of industry research.

Opportunities for industry research on machine components will need to be prioritised and based on machine purpose and design considerations. For example green versus whole-of-crop, wide-swath machine etc. Based on the foregoing discussion, the key tasks required in RDE on machine components are:

a) In harvesting systems where the differentiation and removal of tops and green leaf is required an improved topping system will be required (dry leaf with cane, green leaf rejected).
b) The current crop divider linkage system tends to be dynamically unstable. An industry-led, simple, cost-effective solution (dynamically stable) for controlling the height of the crop-dividers should be encouraged.

c) Evaluation of the impact of volumetric capacity and feeding efficiency when harvesting for high biomass systems (whole-of-crop, high pour rate).

d) Initiation of a program for assessment of alternative concepts for cutting and billeting of sugarcane within the context of minimising percentage loss per cut per metre. Environmental considerations from the impact of sugar juice entering waterways causing de-oxygenation may drive this development.

e) The impact of current industry pour rates on feed train/chopper system configurations and cleaning systems with a particular emphasis on resulting damage and sucrose losses is a priority.

f) In harvesting systems (e.g. whole-of-crop harvesting and/or wide-swath harvesting) where delivery capacity of elevators is a limitation then alternative developments should be assessed.

3. Industry research has demonstrated that there is potential to increase industry profitability without capital investment through reduction in field losses of cane and juice during harvesting. This outcome has been demonstrated and confirmed in overseas industries. Adoption of HBP has been slow due to industry skepticism about sugar loss levels and pressure to minimise extraneous matter and transport costs. The invisible nature of the sugar loss makes it difficult to convince some industry stakeholders of the importance of HBP. HBP should be a priority for the industry as the benefits have been defined.

Based on the foregoing discussion, key tasks are required in RDE to facilitate adoption of HBP practices. These are as follows:

a) Standardised method of testing – mass balance v direct methods.

b) Assessment of sucrose loss from machine process modifications in retro-fit developments and embodied in late model machines e.g. Anti-vortex, 12 blade chopper systems.

c) However, educating the industry of the drivers of HBP and that there is no prescriptive setting to minimise EM and cane loss.

d) The benefits achievable from HBP operation and the costs incurred by harvester operators need to be clearly defined, and a payment system which rewards operators for adopting HBP thus enabling the industry to realise the financial benefits.

e) Real-time and accurate feedback is required to overcome the existing harvester-payment system and enable negotiation of the best possible job at an acceptable price for individual blocks.

f) Progress in harvester development depends on the reliability of performance testing. This includes cane and sucrose loss measurement, not only in test facilities, but also in the field. A method to quickly and accurately measure cane loss directly from field residue samples would have a big impact on harvester performance assessments, fine tuning of machines and driving widespread adoption of HBP principles.
4. Various harvester performance technologies have been researched and developed to provide machine performance feedback or automate machine operations to favour higher harvesting efficiency and higher sugar recovery. Machines still lack the performance quality feedback when compared to other harvesting equipment – both cane supply and infield job.

A number of key enabling technologies are required to allow implementation of HBP practices, harvest and transport integration and provide quantifiable data for value chain analysis. These are as follows:

a) Development of an adaptive on-the-go machine component control system.

b) Further development of real-time systems for reporting of product quality and standardising performance monitoring systems to include not only machine state but HBP feedback inclusion. Any feedback system requires accurate, real-time feedback on incoming cane quality. i.e. NIR.

c) Dirt in cane and basecutter damage are current industry issues. Evaluation of automatic basecutter height control systems – such as the pressure based Auto Tracker/TechAgro and development of a mechanical basecutter height control system similar to the Brazilian Floating basecutter suitable for the Australian Industry should be considered.

5. Over the last few years there has been a ground swell to move towards a more inclusive model of R&D industry research. Value chain models are well developed and from a modelling perspective, there should be minimal “foreseen” further research required at the harvesting transport interface.

The quantitative benefits of value chain research such as reduced harvesting costs and reduced sugar losses have been made difficult by the lack of quality data and due to the rapid changes in harvesting and transport systems (e.g. major fluctuations in cane yield and harvester numbers). Therefore a key task RDE is as follows:

a) Development of a quantitative evaluation methodology that is effective for value chain research. Uncertainty in the system and a moving baseline will need to be accommodated. Harvesting and transport system can change rapidly with fluctuations in cane yield, harvester numbers and implementation of new farming systems.

Simultaneous to all these activities will be the need to keep abreast of overseas developments in harvester components and performance. Support for grower, consultant and researcher visits to technical meetings, centres of expertise and manufacturers to assess new, ‘ready-to-apply’ developments would therefore be highly valuable.

Reference to commercial products or trade names in this report is made with the understanding that no discrimination is intended and no endorsement is implied by the authors.
# Table of Contents

**Document Status Record** ........................................................................................................... i

Executive Summary .......................................................................................................................... iii

Table of Contents ............................................................................................................................ vii

List of Tables .................................................................................................................................... x

List of Figures ................................................................................................................................... x

List of Photographs .......................................................................................................................... xi

Acknowledgements .......................................................................................................................... xii

## 1 Introduction ............................................................................................................................... 13

## 2 Machine Definition .................................................................................................................... 18

2.1 Purpose ....................................................................................................................................... 18

2.1.1 Burnt Cane Harvesting ........................................................................................................ 18

2.1.2 Green Cane Harvesting ......................................................................................................... 19

2.1.3 Whole-of-Crop Harvesting ................................................................................................... 19

2.1.4 Summary ............................................................................................................................... 21

2.2 Design Considerations ............................................................................................................... 22

2.2.1 Row Spacing ....................................................................................................................... 22

2.2.2 Wide-swath Harvesting ......................................................................................................... 26

2.2.3 Weight ................................................................................................................................... 29

2.2.4 Engine Size .......................................................................................................................... 30

2.3 Summary .................................................................................................................................... 30

## 3 Crop Handling Criteria and Components ................................................................................. 31

3.1 Topper ......................................................................................................................................... 31

3.1.1 Research Opportunities ....................................................................................................... 32

3.2 Gathering System ...................................................................................................................... 33

3.2.1 Floating Sidewalls ................................................................................................................. 35

3.2.2 Height Control ....................................................................................................................... 35

3.2.3 Side Trim Knives .................................................................................................................... 37

3.2.4 Benefits Delivered ................................................................................................................. 37

3.2.5 Research Opportunities ......................................................................................................... 38

3.3 Forward Feeding ......................................................................................................................... 38

3.3.1 Knockdown Roller ................................................................................................................ 40

3.3.2 Finned Roller ........................................................................................................................ 41

3.3.3 Benefits Delivered ................................................................................................................. 42

3.3.4 Research Opportunities ......................................................................................................... 42

3.4 Basecutters .................................................................................................................................. 43
3.4.1 Basecutter Angle ................................................................. 43
3.4.2 Basecutter Speed .............................................................. 44
3.4.3 Basecutter Disks ................................................................. 46
3.4.4 Basecutter Blades .............................................................. 47
3.4.5 Benefits Delivered ............................................................ 48
3.4.6 Research Opportunities ...................................................... 48

3.5 Feed Train .............................................................................. 49
3.5.1 Roller Design ....................................................................... 51
3.5.2 Benefits Delivered ............................................................. 52
3.5.3 Research Opportunities ....................................................... 52

3.6 Billeting System ......................................................................... 53
3.6.1 Benefits Delivered ............................................................ 61
3.6.2 Research Opportunities ....................................................... 61

3.7 Primary Cleaning System ......................................................... 61
3.7.1 Hood Designs ...................................................................... 63
3.7.2 Modelling of Primary Cleaning Chamber .......................... 64
3.7.3 Current Designs ................................................................. 65
3.7.4 Counter Rotating Fans ........................................................ 67
3.7.5 Alternative Cleaning System Designs ................................ 67
3.7.6 Benefits Delivered ............................................................ 69
3.7.7 Research Opportunities ....................................................... 69

3.8 Elevator .................................................................................. 69
3.8.1 High-speed Elevator .......................................................... 70
3.8.2 Elevator Modifications ........................................................ 71
3.8.3 Benefits Delivered ............................................................ 73
3.8.4 Research Opportunities ....................................................... 73

3.9 Secondary Cleaning .................................................................... 73
3.9.1 Blower Cleaning System .................................................... 73
3.9.2 Benefits Delivered ............................................................ 75

3.10 Instrumentation and Controls .................................................. 76
3.10.1 Ergonomic Cabin ............................................................... 76
3.10.2 Benefits Delivered ............................................................ 77

3.11 Benefits Delivered from Component Research .......................... 77
3.12 Machine Component Research Opportunities .......................... 78

4 Harvester Performance – The Yield v Quality Imperative .............. 80

4.1 Loss Processes .......................................................................... 80
4.1.1 Quantifying Loss ............................................................... 81
4.1.2 Methods to Measure In-Field Sugar Loss ............................ 82

4.2 Topper Loss ........................................................................... 84
4.3 Gathering and Pick-up loss ...................................................... 84
4.4 Basecutter and Feed Train Losses ........................................... 85
4.5 Chopper Losses and Billet length .......................................... 86
4.6 Cleaning Chamber Losses ...................................................... 91
4.7 Benefits Delivered ............................................................... 95
4.8 Research Opportunities ................................................................. 96

5 Harvesting Best Practice (HBP) ....................................................... 97

5.1 Feed Train/Chopper Optimisation ................................................ 97
5.2 Extractor Loss and Extraneous Matter ........................................ 98
5.2.1 Fanspeed ................................................................................ 98
5.2.2 Pour Rate ................................................................................ 98
5.2.3 Payment Systems ................................................................... 103
5.3 Benefits Delivered ....................................................................... 105
5.4 Research Opportunities ............................................................... 106

6 Harvester Performance Monitoring .................................................. 107

6.1 Real-Time Monitoring Systems .................................................. 108
6.1.1 Basecutter Height Control ....................................................... 108
6.1.2 Cane-Loss Monitor ................................................................. 112
6.1.3 Cane-Yield Monitoring ........................................................... 115
6.1.4 Sugar-Yield Monitoring ............................................................ 117
6.1.5 Harvester Performance Monitoring ......................................... 118
6.1.6 Crop-Handling Speed Control System .................................... 121
6.2 Benefits Delivered ....................................................................... 123
6.3 Research Opportunities ............................................................... 123

7 Harvest and Transport Integration .................................................. 125

7.1 Harvest Monitoring ..................................................................... 125
7.1.1 Benefits Delivered .................................................................. 127
7.1.2 Research Opportunities ......................................................... 127
7.2 Value Chain Analysis .................................................................. 128
7.2.1 Benefits Delivered .................................................................. 129
7.2.2 Research Opportunities ......................................................... 130

8 The State of Play in the International Sugar Industry ......................... 132

8.1 Brazil .......................................................................................... 132
8.2 Columbia .................................................................................... 135
8.3 Florida ........................................................................................ 135
8.4 Louisiana ....................................................................................... 135
8.5 Argentina ..................................................................................... 137
8.6 Benefits Delivered ....................................................................... 138

9 Conclusions and Recommendations ............................................. 139

10 References .................................................................................. 142

11 Bibliography ............................................................................... 156
LIST OF TABLES

Table 1: Relative Energy Value of Sugarcane Biomass (Norris 2004) ...........................................20
Table 2: Effect of Billet Length Upon Bin Weight (James 2003) ................................................90
Table 3: Comparison of harvesting best practice versus ‘normal’ operation (Whiteing et al. 2002) ..............................................................................................................101
Table 4: Payment calculations from a HBP trial (Stainlay, unpublished) ..................................102

LIST OF FIGURES

Figure 1: 1.5 m Row Spacing – 1.85 m Wheel Spacing ..........................................................23
Figure 2: 1.85 m Wheel Spacing – Single Row ........................................................................23
Figure 3: 1.85 m Wheel Spacing - Dual Row ........................................................................24
Figure 4: 2 m Wheel Spacing- Dual Row – 800 mm Spacing .....................................................24
Figure 5: 2.4 m Wheel Spacing – Dual Row – 1200 mm Spacing .............................................25
Figure 6: 3 m Wheel Spacing – Two Single Rows – 1500 mm Spacing ...................................25
Figure 7: Layout of Australian Standard ‘Chopped Cane’ Sugarcane Harvester .................31
Figure 8: Cane Failure Curves and Location of Forward Feeding Components (Kroes and Harris 1996) ........................................................................................................41
Figure 9: Maximum Permissible Forward Speed versus Blade Wear (Kroes 1996) .................45
Figure 10: The Optimum Harvester Forward Speed (Kroes 1996) ........................................46
Figure 11: Schematic Side view of the Bonel Prototype Chop-Throw Harvester (Norris 2000) .........................................................................................................................54
Figure 12: Airflow Distribution of a Primary Extractor (4ft 6inch) Cleaning System (Davis 2002) .........................................................................................................................62
Figure 13: Blower cleaning System High-Speed Elevator (Davis and Norris 2001) ..............75
Figure 14: The Interacting Effects of Fan Speed and Billet Length upon Sugar Yield (James 2003) ......................................................................................................................89
Figure 15: The Estimated Effects of Billet Length and Diameter upon Average Bin Weights for Mossman High Sided Bins (James 2003) ......................................................90
Figure 16: ‘Blue Tarp’ versus Mass Balance Fanspeed Trial (Whiteing et al. 2002) ...............93
Figure 17: Probable cane loss versus fan speed (Whiteing et al. 2002 (Left)) Gomez et al. 2006 (Right) ...............................................................................................................94
Figure 18: Percentage Cane Component of Total extracted Material (Whiteing et al. 2002) .........................................................................................................................................95
Figure 19: Effect of Fan Speed on CCS and Grower Returns (Whiteing 1997) ....................98
Figure 20: Effect of Pour Rate on Trash and CCS Levels (Whiteing et al. 2002) .................99
Figure 21: The Effect of Pour Rate and Extractor Fan Speed on Final Trash Levels in Cane (Whiteing et al. 2002) .................................................................................................100
Figure 22: Characterisation of Extractor Performance for Pour Rate and Fan Speed in ‘Average’ field Conditions (Whiteing et al. 2002) .........................................................100
Figure 23: TechAgro Onboard Computer System for Automatic Basecutter Height Control .................................................................................................................................111
Figure 24: CASE IH AutoTracker Display (Left) and Basecutter Pressure Sensors installed on Harvester (Right) ...............................................................................................112
Figure 25: Pressure Transducer to Monitor Chopper Pressure (Left) and LVDT to Measure Feed Train Roller Displacement (Right). .........................................................116
Figure 26: Crushing Mechanism Mounted on Topper Arm, and Close-Up View of Crushing Mechanism (Inset) (McCarthy and Billingsley 2002) ........................................118
Figure 27: AgGuide Harvester Monitoring Unit .............................................................. 119
Figure 28: AgTrix Pty Ltd Conceptual HBP Expert System .......................................... 120
Figure 29: GPS Harvester Tracks in a Harvested Field, Coloured by Speed (Beattie and Crossley 2006) .......................................................................................................... 126
Figure 30: Brazil Centre-South Region – Sugar versus Ethanol split (Romanach 2007) ....................................................................................................................... 133

LIST OF PHOTOGRAPHS

Photograph 1: 1971 Mizzi Double Row Prototype (Powell 2006) ................................. 26
Photograph 2: Prototype Cameco 2-Row Cane Harvester (Right) (DAVco Farming 2006) ......................................................................................................................... 27
Photograph 3: Modified EHS Dual row Harvester ............................................................ 27
Photograph 4: Corradini Two-in-One® ............................................................................ 28
Photograph 5: John Deere 3500 Series Gathering System with Optional Outer Spiral and Throat Rollers .......................................................... 35
Photograph 6: Whole-of-Crop Harvesting Crop Divider Side Trim Knives (Left) and Side Trim Knife Operation (Right) .............................................................. 37
Photograph 7: BSES Chopper Test Rig ........................................................................... 50
Photograph 8: Cannavan’s Chop-Throw Harvester-1966 (Left) and BONEL Chop-Throw Harvester (Right) .......................................................... 54
Photograph 9: EHS Manufacturing Prototype 12 Blade Rotary-Pinch Chopper Drum ... 59
Photograph 10: John Deere 3510 (5 Ft) Primary Extractor Fan ....................................... 65
Photograph 11: Anti-vortex Fan ....................................................................................... 66
Photograph 12: ‘Flipper’ Roller Elevator Extension ......................................................... 72
Photograph 13: Elevator Extension Conveyor (Left) and Extended Elevator (Right) ...... 72
Photograph 14: Sugarcane H-E-L-P Fuel Saver System (Sugarcane H-E-L-P Services 2009) .................................................................................................................. 121
Photograph 15: PLC Interface (Left) and Eaton Electro-Hydraulic PV54 Pump Controller (Right) (Whiteing and Kingston 2008) ................................................................. 122
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This report has been written predominately using the authors’ experiences in sugar and related industries and unpublished and published information on ‘chopped cane’ sugarcane harvester design and performance that are being applied or could be applied to improve the cost efficiency and reduce the environmental impact of sugarcane harvesting and transport.

These technologies have been made more accessible within the Australian sugar industry due to the generous financial support of the Sugar Research and Development Corporation (SRDC) through industry and grower/harvesting group projects, Queensland government through reform programs such as the Sugar Industry Innovation Fund (SIIF) and countless other industry, government and privately funded projects.

Funding for this review, analysis and forum discussion was provided by the SRDC and was carried out in consultation with many people involved with sugarcane harvesting both domestically and internationally. The project team extend their appreciation to all these people who provided input into the project.
1 INTRODUCTION

In the early stages of the Australian sugar industry, sugarcane was cut by hand and there was an on-going struggle to obtain labour for harvesting.

Although experimental machines began cutting cane as early as the 1920s, the industry depended heavily on manual cutters until well into the mid-1960s. Tentative moves towards mechanisation accelerated after World War II as capable hand cutters became increasingly difficult to obtain for the expanding harvest.

Until the 1940s most cane was cut green by hand cutters with residual trash burnt on the ground. Burning prior to harvest became standard practice due to outbreaks of the potentially fatal Weil’s disease, labour shortages and the ability of manual cutters to cut and load burnt cane faster than unburnt cane.

Wholestalk harvesting machines were being used as early as 1944 but initially they did not have a major impact on the harvesting process and did not have a significant role until the 1960’s. Mechanisation was given a strong boost by the advent of mechanical loaders. By 1957 around 30% of the crop was being loaded by machines and by 1962 this had increased to 65%.

The pioneering ‘chopped cane’ harvester was the Massey Ferguson 515, side mounted on a farm tractor. From 1956 onwards ‘chopped cane’ harvesters began to take over from wholestalk machines. The was due to their ability to handle lodge crops in north Queensland and the Burdekin combined with their ability to cut and load, thus eliminating the extra loading step required with wholestalk machines. These machines were well established by 1965.

By 1975 around 98% of the crop was cut by ‘chopped cane’ harvesters. In 1979 Australia became the first sugar producing nation to convert entirely to mechanical sugarcane harvesting. Therefore, the Australian industry has the longest experience with mechanisation of any sugarcane growing country.

Pre-harvest burning was standard practice until the early 1980s when some growers began to experiment with green cane harvesting and associated trash blanketing. The agronomic benefits of trash blanketing, combined with greater harvesting flexibility in wet weather, prompted the development of new technology.

The Australian type ‘chopped cane’ sugarcane harvester is a single row, over-the-row machine with a swinging elevator capable of delivering sugarcane to either side or to the rear of the harvester. The basic principles used in ‘chopped cane’ sugarcane harvesters have not changed significantly since they were first developed. The main changes are related to improved feeding and cleaning during green cane harvesting and increased capacity.

The evolution of the ‘chopped cane’ sugarcane harvester in Australia has been a unique blend of the developments of innovative farmers, small manufacturers, and the research and development teams of larger corporations.

Massey Ferguson was one of the earliest manufacturers of ‘chopped cane’ sugarcane harvesters in Australia. The company’s background in the design of tractors and grain
harvesting machinery meant that the research and development program by its cane harvester division followed a somewhat different and less reactive process to that of its competitors. It is noted that some ideas from Massey Ferguson, notably the rotary-pinch chopper system and basecutters were adopted by its competitors in later models.

By the early 1970’s, the Australian ‘standard’ sugarcane harvester design was well-established by machines such as the Toft 3000, MF102 and Mizzi (Norris et al. 1998b). The pioneering Massey Ferguson, Toft and Mizzi harvesters have been replaced by successive models of Case IH Austoft (formerly known as “Austoft”, "Toft", "Versatile Toft", "International Toft" and "Toft Brothers") and John Deere (formerly known as “Cameco”) harvesters. Modern harvesters incorporate hydraulic drives and electronic controls for all functions, and use extractor fans for primary and secondary cleaning.

By the mid 1970’s, the agronomic advantages of harvesting green cane were beginning to be assessed by industry. Class introduced a number of green cane machines (Claas 1400) into the industry in 1976 which initiated development of green cane machines by Australian manufacturers. The Claas 1400 with engine power of 125kw and rotary-pinch chopper system was well respected for performance in green cane, especially feeding ability, billet quality and basecutter cut.

Hence, early investigations into ‘chopped cane’ harvester performance were centred on green cane harvesting ability and loss comparisons with burnt cane harvesting. The work by Foster et al. (1977), Mason et al. (1978), Fuelling et al. (1978) and Foster (1979) compared commercial cane sugar (CCS), extraneous matter (EM), pour rate and cane loss between Claas 1400, Toft (6000) and Massey Ferguson (MF205) machines operating in both green and burnt cane. Fuelling (1982) also highlighted that there was a strong correlation with the decline CCS and sugar production per hectare decline and the introduction of the chopper harvester. Against this background, the harvester manufacturing industry was developing the conceptual requirements for new machines.

By the late 1980’s, research was still centred on performance evaluation of machines in green cane harvesting with Ridge and Dick (1988), Stewart and McComiskie (1988) and Shaw and Brotherton (1992) investigating throughput, EM and cane losses during cleaning. However, there was also a new focus, dirt in the cane supply. Ridge and Dick (1988) also investigated dirt rejection by harvesters.


Throughout this period ongoing cane quality (EM/Dirt) issues and cane losses were evaluated by Linedale and Ridge (1996), Fuelling (1999) and Schembri et al. (2000). Whiteing and Norris (2002) and Whiteing et al. (2002) undertook fundamental investigations into the effect of fan speed and pour rate on cane loss and EM.

Over the past few years the research focus has been on harvest system modelling (e.g. Higgins and Langham (2001), Antony et al. (2003), Higgins and Davies (2004), Sandell and
Mechanical harvesting of sugarcane has been a major success story for the Australian sugar industry. However, the Australian sugarcane industry has suffered a plateau in productivity (Wilson and Leslie 1997) and there is considerable evidence that mechanisation is a component of this.

The Australian sugar industry has recently faced an unprecedented cost-price ‘squeeze’ from a run of poor seasons, the collapse of the international price of raw sugar and a strengthening currency. While the situation has recently abated, there is no doubt that the long term outlook for sugar prices is more pessimistic than in recent decades. Faced with this situation, the industry must become more efficient at producing raw sugar and look for alternative activities, or undertake what Hamel and Prahad (1994) describe as “getting better and becoming different”. Much attention has been given to improving harvesting productivity and profitability in the industry, both through research (e.g. Davis and Norris (2002a), Norris et al. (2000), Higgins et al. (2006), Crossley and Dines (2004), Whiteing et al. (2002), Wood et al. (2003)) and extension (e.g. Linedale and Ridge (1996), Agnew (2002), Juffs et al. (2004)) – these efforts being aimed at getting better. One dimension of becoming different is consideration of alternative products from the raw sugar production value chain. For example, whole-of-crop harvesting to maximise co-generation will challenge the traditional logistical operation of the value chain.

The design and development of the basic Australian type ‘chopped cane’ sugarcane harvester (single row, swinging elevator delivering cane to either side or to the rear of the harvester) has evolved from farming practices of the 1970’s (i.e. 135 kW (180 Hp), burnt cane, 1.5 m rows). There has been no increase in volumetric capacity (machine throat size, 900 mm feed train/chopping system) of machines.

The increase in machine pour rate over this time has resulted in an increase in cane matt thickness and speed. This increase in machine capacity has been achieved mainly by supplying extra power to critical areas such as the basecutters and chopping system and doubling engine size to 279 kW (375 Hp).

Aggressive gathering, knockdown and feeding components and poorly adjusted and blunt blades damage stool and cane. Current harvesters with up to 375 Hp can have delivery rates in excess of 100 t/hr delivered to the siding. Therefore, pour rate off the elevator must be approaching 200 t/hr but with considerable billet damage and loss of high-pol juice. At high pour rates of cane through the harvester, the ability of the machine to clean the cane without losing considerable amounts of cane is limited. The chopper systems in particular are not designed to handle high pour rates of cane. Current harvest payment arrangements encourage high pour rates.

There is no simple solution to this complex issue. In the context of raw sugar production it is vital that as much of the sugar in every hectare of sugarcane is converted into saleable product leaving the mill. Similarly, this should also underpin diversified production streams. Although there are additional challenges of determining if the logistical problems of handling increased volumes of material in the harvesting and transport sectors and the negative impacts at the farm and mill factory were out weighed by the additional revenue from increased production of electricity for export.
Therefore, that success story now presents the Australian industry with a major opportunity, and a major challenge to realise that opportunity, as it seeks to meet the international competition of the 21st century (SRDC 2004).

In recent times the industry has been striving to improve the efficiency and productivity of its sugarcane harvesting and transport practices. Particular goals are to improve cane and sugar yields through better harvest scheduling and by reducing cane and juice losses during harvesting.


Whilst the HBP manual is the premier document of mechanised harvesting, it also highlights the lack of scientific data on many of the critical components of the mechanised harvesting and transport systems.

In 2004, SRDC funded an analysis of the benefits and costs to different participants across the value chain for implementing better harvesting practices. This was aimed at achieving greater ownership of the magnitude of sugar losses with mechanical harvesting and to encourage novel industry-led approaches to reduce harvesting losses.

SRDC has provided significant investment in harvester technology and harvesting operations aimed at developing and implementing innovative technology and best management practices. This was used for enhancing revenue, improving capital utilisation and environmental performance in harvesting and transport. Current industry issues of sucrose losses, cane supply quality, alternative farming systems (1.83m to 2m row spacing) and whole-of-crop harvesting have further highlighted the limitations with current harvester designs.

This has renewed interest at a grower and regional level for improved harvester designs and harvesting practices. SRDC continues to receive requests from industry to support harvester research and development.

This review will integrate the research which has been undertaken to improve harvester and harvesting performance including:

- Identifying the benefits delivered
- Opportunities to improve the design and performance of harvesters
- Opportunities to reduce costs of harvesting and increase the recovery of sugar during the harvesting operation.
- Identify where future R&D would benefit the industry for harvester design and performance

The outcomes will be an informed knowledge base on which industry can draw on as it moves forward, and on which SRDC can draw on in making decisions on further research in harvesting R&D.

The harvesting process requires the various participants to optimise many interacting processes. Three classes of factors affect the efficiency of harvesting. These include farm
factors (e.g. row profile, soil types, layout, haul distances), harvester machine factors (e.g. chopper losses) and farming system (e.g. pour rate, group size, burnt cane, green cane and whole of crop harvesting).

However, harvesting efficiency is a complex process that involves many compromises and provides numerous opportunities. Farm factors that might conceivably impact on harvester performance include row profile, row spacing, farm layout, topography, cane variety, weed pressure, crop lodging etc.

While not necessarily simple, cheap or fast to implement, these factors each contribute to overall harvest efficiency. However, only a few are amenable to immediate or short-term change such as row profile, row spacing, farm layout, cane variety. Others are the result of chance events that may be beyond the control of the grower such as soil conditions – wet/sticky, crop conditions - lodging, density etc.

Most of these factors listed clearly contribute to the performance of the harvester and to overall harvesting efficiency. Their importance in the harvesting process is not diminished. However, for the purposes of this review the focus is on machine (e.g. gathering, feeding, basecutter, chopper, cleaning components) and farming system (e.g. pour rate, payment system, field efficiency) factors that might conceivably affect the performance and efficiency of the basic Australian type ‘chopped cane’ sugarcane harvester.
2 MACHINE DEFINITION

The purpose of the Australian ‘chopped cane’ sugarcane harvester needs to be outlined and what it needs to do must be clearly defined. The purpose will guide the review of the basic design concepts and criteria incorporated into the design of the machine and ultimately leading to identified opportunities to improve design and performance.

The sugarcane harvester fleet in Australia consists entirely of single, over-the-row ‘chopped cane’ harvesters with swinging elevator capable of delivering sugarcane to either side or to the rear of the harvester.

2.1 Purpose

The ‘chopped cane’ harvester is a machine that combines the task of harvesting and cleaning sugarcane crops. The ‘chopped cane’ harvester performs the basic functions of gathering and topping cane, severing stalks at ground level, feeding cane through a chopper system where it is cut into billets and delivering chopped cane directly into infield transporters. Depending on the cane harvesting requirements the machine may perform the additional functions of removing as much dirt, leaf and trash as possible from the cane supply (Ridge and Norris, 2000).

Sugarcane can be harvested burnt, green or the whole crop. These requirements are outlined in the following sections.

2.1.1 Burnt Cane Harvesting

Until the 1940’s, most of the Australian sugarcane crop was hand cut green, with residual trash being burnt on the ground. Burning prior to harvest was allowed in some mill areas to control Weil’s disease (Leptospirosis). The shortage of labour, together with the increased output of manual cutters in burnt cane, led to burning becoming standard practice after World War II.

Burnt cane harvesting involves burning the sugarcane before it is harvested. This removes leaves, weeds, and other matter, which can impede the harvesting and milling operations.

Pre-harvest burning persisted as the standard practice until the early 1980s when some growers began to experiment with mechanical green cane harvesting and associated trash blanketing. In the Burdekin region and New South Wales the crop is predominantly burnt prior to harvest. The percentage of burnt cane harvested in the Burdekin region was 94.3% of 8,225,415 tonnes and New South Wales 92% of 2,174,886 tonnes in 2007 respectively. This is substantially higher than the industry average.
2.1.2 Green Cane Harvesting

Green cane harvesting and associated trash blanketing involves harvesting the sugarcane green and separating the dry and green leaf and tops from the cane. The aim is to minimise the amount of trash harvested with the cane and allow the separated material to fall to the ground to act as a protective trash blanket.

Machine design elements have to be changed to meet the requirements for harvesting green cane when compared to burnt cane. The two most important points are that the volumetric capacity of the machine must increase and the feed efficiency must increase so that choking or glut feeding is minimised.

The use of this trash blanket as an organic mulch considerably reduces the level of soil erosion and preserves soil nutrition for crop growth. It also helps to prevent weed germination, reducing the need for herbicides. The agronomic benefits of trash blanketing, combined with greater harvesting flexibility in wet weather, prompted the development of new technology.

However, districts with high yielding one-year or two-year crops such as the Burdekin and northern New South Wales have largely avoided green cane harvesting because of harvesting difficulties and agronomic constraints. Green cane harvesting has expanded gradually since the 1980’s, reaching 70.5% of the total crop harvested (34,125,022 t/cane) in 2007. The percentage of green cane harvested in the Burdekin region (5.7% of 8,225,415 tonnes) and NSW (8% 2,174,886 tonnes) is substantially lower the industry average.

Significant overseas sugarcane industries (e.g. Brazil) have yet to embrace green farming systems. Therefore there is still a large market for burnt cane machines.

2.1.3 Whole-of-Crop Harvesting

Diversification from ‘traditional’ sugar production within the industry has focused on production of renewable energy from ethanol or electricity co-generation (Keating et al. (2002); Sutherland (2002)). Undertaking these ventures entails new challenges for the traditional organisation of the sugarcane supply chain. Other possible new enterprises, such as the production of fibre-based products (paper, packaging, etc.) or lactic acid (Allen et al. 1997), pose similar challenges. Feedstocks for these processes are required at different times and possibly from different sources from those associated with ‘traditional’ sugar production in Australia.

Green cane harvesting leaves large amounts of trash (sugarcane dry and green leaves, and tops) for energy purposes. A significant increase in recoverable energy is achievable by incorporating a proportion of the trash in the cane supply, and separation of that trash at the mill prior to milling. The relative energy content of different components of a crop with a nominal yield of 105 t/ha is given Table 1.

The dry and green leaves and tops represent about one-third of the total mass for commercial sugar cane. Dry leaf trash has about double the net heat energy of bagasse and about three times that of green leaves and tops. Hence, the dry leaf component is a
significant energy resource and can represent a significant energy capture. The research into high fibre ‘energy’ sugarcane is leading to the development of more erect varieties. Table 1 indicates that the recoverable energy value (LHV) of the composite residues at time of harvest is about that of the bagasse, the traditional source of energy. The mass of the residues at harvest is approximately 34 t/ha, and the moisture content of the composite residues would be approximately 51%.

**TABLE 1: RELATIVE ENERGY VALUE OF SUGARCANE BIOMASS (NORRIS 2004)**

<table>
<thead>
<tr>
<th>Component</th>
<th>Initial MC%</th>
<th>Initial Mass (t/ha)</th>
<th>Energy Content (MJ/kg)</th>
<th>Total Energy @ Harvest (GJ/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clean cane</td>
<td></td>
<td>105</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tops</td>
<td>80</td>
<td>9.2</td>
<td>1.4</td>
<td>13</td>
</tr>
<tr>
<td>Green Leaf</td>
<td>66</td>
<td>14.0</td>
<td>4.2</td>
<td>59</td>
</tr>
<tr>
<td>Dry Leaf</td>
<td>12</td>
<td>10.8</td>
<td>15.1</td>
<td>162</td>
</tr>
<tr>
<td>Composite Residue</td>
<td>51.3</td>
<td>33.9</td>
<td>6.9</td>
<td>234</td>
</tr>
<tr>
<td>Bagasse</td>
<td>50</td>
<td>27.3</td>
<td>7.4</td>
<td>201</td>
</tr>
</tbody>
</table>

Typically, the two strategies used for whole-of-crop harvesting are green cane harvest with all material (cane and trash) transported to the mill and conventional green cane harvest with post harvest collection (baling). Typically, the additional fuel sourced from either of these two strategies is used to fuel co-generation plants.

Whole-of-crop harvesting represents a paradigm shift to the traditional burnt cane or green cane harvesting supply chain and challenges the traditional logistical operation of the supply chain. The principal of whole-of-crop harvesting is to maximise the production of co-products such as electricity, ethanol and/or paper.

In light crops, harvesting the whole-of-crop gives higher machine productivity when compared with green cane harvesting. However, in large crops, machine productivity is similar to green cane harvesting due to limitations in volumetric capacity and feeding efficiency. The amount of material to be transported from the harvester to the mill increases. If the whole-of-cane product is milled this significantly reduces the processing rate and efficiency of sugar extraction in the milling process (Shaw and Brotherton 1992). Trash quality (mainly alkali levels) may be a decisive factor for its utilisation in co-generation equipment.

At the mill, whole crop harvesting requires substantial investment in new infrastructure for maximising electricity production (increased generation capacity, upgrading mill components, etc.). New infrastructure may also be required for separation of trash and cane at the mill prior to crushing the cane to minimise the impact on mill efficiency (Cargnello and Fuelling (1998); Schembri et al. (2002)).
Further analysis indicates that the mass of dry leaf at time of harvest is less than 30% of the total residues mass, however the recoverable energy is approximately 70% of the total from all residues, and approximately 80% of the energy available from bagasse. Clearly, a harvesting operation which results in predominantly dry leaf being available as a supplementary fuel maximises the benefit of trash recovery for supplementary energy.

At the farm level, retaining trash on the soil surface trash increases sugarcane yields in many environments (Thorburn et al. 2004), and so its removal may impact the amount of material (cane and trash) available for processing, and hence products (sugar and electricity) available for sale. The approach should be to retain the green portions of trash (by topping and shredding) on the field for agronomic advantages and utilise the dry leaf trash as fuel. The dry leaf trash has the least value in the field and the highest energy value as fuel. In addition, the dry leaf trash component has nowhere near the impact on bin weight when compared to green portions of trash and has a lower level of total alkali than the green portions of trash (and similar to bagasse).

The challenge for whole-of-crop harvesting is in the logistical problems of handling increased volumes of material in harvesting and transport sectors.

This manifests itself through the harvester’s inability to cut large crops (quantity versus quality imperative) and the additional volume (a lower bulk density) of the harvested material reducing the mass of material carried by infield and subsequent rail or road transport. Whole-of-crop harvesting is the centrepiece of the New South Wales sugar industry’s diversification into electricity cogeneration. Cogeneration is both economically beneficial for the NSW Sugar Milling Cooperative (NSWSMC) and its grower members, and provides environmental and social benefits to the communities, which coexist with the region’s sugar industry.

2.1.4 Summary

- Green cane harvesting has expanded gradually reaching 70.5% of the crop harvested in 2007. The percentage of green cane harvested in the Burdekin region (5.7%) and NSW (8%) is substantially lower the industry average. These areas also have high yielding crops. Machine design elements have to be changed to meet the requirements for harvesting green cane when compared to burnt cane.

- Significant industries overseas have yet to embrace green and whole-of-crop systems, so from a manufacturer’s perspective burnt cane is still a significant market for machines, and for machines in new industries. Although green cane harvesting is becoming more important as environmental considerations become paramount.

- Product diversification of sugarcane must be further encouraged, in order to increase returns. As the industry moves towards diversification opportunities, challenges in machine design and performance will need to be met.

- The industry should analyse the machine design requirements for whole-of-crop harvesting.

- The industry should investigate options for handling increased volumes of material in harvesting and transport sectors with whole-of-crop harvesting.
2.2 Design Considerations

There are two major issues facing the Australian sugar industry that may lead to significant changes in harvester design and harvesting systems. These are new farming systems and the cost of harvesting.

A sugarcane farming system based on residue retention, minimum tillage, a leguminous rotation crop and controlled traffic using global positioning system guidance is currently being adopted by the Australian sugar industry. It improves sugar yields, reduces costs and provides additional income from crops such as soybean and peanut.

During the last decade the harvesting sector has faced an unprecedented cost-price squeeze from rising capital, parts and fuel costs and labour availability. This has been compounded by a run of poor seasons which has impacted on harvester productivity.

The harvesting sector is responding to these issues through a number of alternative design considerations to the standard Australian machine. These include modifications to suit a number of row spacings and wide-swath harvesting.

2.2.1 Row Spacing

The Australian sugar industry is currently adopting a new farming system based on controlled traffic, reduced-tillage and fallow legume break crops to break disease cycles and reduce compaction. The new farming system is not a one-size fits-all recipe, therefore, there is no standard row spacing. Hence, harvesting manufacturers have not been able to establish a common machine configuration for the industry.

In conventional cane farming systems, cane is grown on rows 1.5 m apart. The Case IH Austoft 7000 and 7700 cane harvesters have a wheel centre of 1860 mm and a track centre of 1880 mm respectively. Case IH 7000/7700 machines built prior to 2003 have a throat width of 900 mm. Machines built after 2003 have a throat width of 1080 mm. The Cameco (2500 series) and John Deere (3500 series) both have a wheel and track centre of 1880 mm. Cameco 2500 series have a throat width of 900 mm whilst, John Deere 3500 series machines have a throat width of 1000 mm. Therefore, current machinery is too much of an agronomic compromise for the current 1.5 m system (Figure 1).

A number of controlled traffic row spacings have been adopted throughout the industry. There are a number of slight variations to these but the most common include 1.85 m row with single row and dual row, 2 m wheel spacing with dual rows at 800 mm centres, 2.4 m wheel spacing with dual rows at 1200 mm and a 3 m wheel spacing dual rows at 1.5 m spacing.

Figure 2 and Figure 3 illustrate the 1.85 m wheel spacing configuration with single and dual rows respectively. This spacing utilises current equipment and only requires minor modifications to the machines. Modifications include widening the gathering system to 1.8 m (1.5 m standard) and extending the length of the elevator by using an attachable elevator extension or extended elevator (600 mm longer than standard). For dual rows the throat width and distance between the basecutter legs may need to be widened. Dual rows allow
about a 23% increase in throughput at the same ground speed, however from an agronomic perspective the dual row at 500 mm is undesirable.
Figure 4 illustrates the 2 m wheel spacing configuration with dual rows at 800 mm spacing. The use of multiple rows is required to improve the crop canopy and maintain yields. This spacing requires extensive modifications to the front–end and elevator of machines. Modifications include widening the gathering system to 2.4 m (1.5 m standard), widening the throat (EHS Manufacturing has widened throats to 1300 mm), widen the basecutter box to 780 mm (standard – 630 mm), widening the wheel spacing to 2 m and extending the length of the elevator. In most cases, the haulout is moved in a row so there is only one row between the harvester and the haulout, therefore avoiding the need for a long and heavy elevator.

Dual rows allow about a 33% increase in throughput at the same ground speed compared to standard configuration and from an agronomic perspective a dual row at 800 mm is acceptable.

Figure 5 illustrates the 2.4 m wheel spacing configuration with dual rows at 1200 mm spacing. There have been no harvesters modified to these specifications. Dual rows allow about a 60% increase in throughput at the same ground speed compared to standard configuration and from an agronomic perspective a dual row at 1200 mm is acceptable. John Deere is currently producing a run of 20 double 1.1 m row harvesters for the Brazilian 1.1 m
row configuration. Brazil currently has about 5% of the total mechanised area on 1-1.1 m rows.

Figure 5 illustrates the 2.4 m wheel spacing configuration with dual rows. This spacing requires either a double row machine with two sets of standard basecutters and two 900 mm feed trains or an alternative dedicated wide-swath machine with wide front, larger diameter basecutters and extended feed train. There are a small number of 1.5 m double row machines in operation. Namely the Young and Greaves double row machines in Bundaberg and the DAVco farming 2-row Cameco “prototype” harvester (Photograph 2). The Cameco 2-row “prototype” is the only double 1.5 m row machine produced by the harvester manufacturers. However, to this date only three of these machines have been built.

This system allows greater than a 100% increase in throughput at the same ground speed compared to standard configuration.

Figure 6 illustrates the 3 m wheel spacing configuration with two single rows at 1.5 m spacing.
The industry must move towards a controlled traffic system and uniform row-spacing to increase production, reduce costs and remain competitive. Therefore, the industry should standardise its row-spacing configuration as has happened in the cotton, vegetable and other industries both in Australia and overseas.

These issues will have a major impact on the design of the basic Australian machine.

### 2.2.2 Wide-swath Harvesting

Powell (2006) highlighted that sugarcane harvesting productivity had flat-lined recently and there were very limited opportunities to increase productivity with a single (1.5-1.6 m) row. He reported that the harvesting sector of the Australian sugar industry generally had been managing costs by increasing tonnes per hour and by running capital out. It is now at the point where an incremental step change is required to further increase harvester productivity.

One of the few options available to the industry to reduce or maintain harvesting costs is to implement a system that can increase the delivery rate of cane – more cane delivered is more income for a relatively constant cost. In recent years, harvesters have reached the limit of increasing delivery rates, due to the capacity of the machines to harvest more cane, farm layout and transport constraints.

It is clear that if a harvester is able to cut a wider swath in each pass, it will increase the delivery rate of cane significantly and, therefore, contain the cost of harvesting. There are, however, some significant constraints to the adoption of wide-swath harvesting.

The concept of wide-swath harvesting was not a new idea. The first recorded wide-swath harvester was developed by Faukner in 1929 in Cuba and the USA. Other investigations into wide-swath harvesting were done by Mizzi, Young and Toft in the 1960/1970s.

**PHOTOGRAPH 1: 1971 MIZZI DOUBLE ROW PROTOTYPE (POWELL 2006)**

Wide-swath harvesting can be defined as any harvesting swath configuration greater than 1.8 m. The Australian sugar industry currently has numerous wide-swath harvesting
configurations - from the machines harvesting single rows on 1.8-1.9 m row configurations, machines harvesting dual rows on 1.8-2.1 m row configurations (EHS dual row), machines harvesting two rows on 1.5 m row configurations (e.g. the Greaves/Young double-row harvester, DAVco Cameco “prototype”), ‘multiplier’ units and Corradini Two-in-One® units. Concept machines exist, such as the Hoban/Mizzi double-row harvester and the Irvin multiple-row harvester. It appears the barrier to adoption of these units has been industry acceptance and/or the cost of the product. In 1999, Cameco built three 2-row “prototype” harvesters, one for Florida, one for Louisiana and one for DAVco Farming as shown in Photograph 2.

PHOTOGRAPH 2: PROTOTYPE CAMECO 2-ROW CANE HARVESTER (RIGHT) (DAVCO FARMING 2006)

EHS manufacturing have modified eight late model harvesters capable of harvesting 1.5 m single row to 2 m (800 mm) dual row. Modifications include widening crop dividers to 1.9 m, widening the throat to 1300 mm and installation of a modified basecutter box with 775 mm leg centres. The feed train, chopper and elevator components remain as standard. All these machines are currently harvesting commercially (S Lawn 2009 pers comm.).

PHOTOGRAPH 3: MODIFIED EHS DUAL ROW HARVESTER
The Corradini Two-in-One® can be retro-fitted onto a harvester that changes the standard single-row configuration to a wider swath width of two rows of sugarcane (on a row spacing of 1.5–1.65 m) to be harvested at one time (Photograph 4). The design, now commercialised is capable of harvesting stands of cane up to 140 t/ha (Di Bella et al. 2005). The intellectual property of the design and concept is protected by Australian patent No. 200 390 2542.

Di Bella et al. (2005) reported that the Two-in-One® had significantly lower fuel costs, lower operating costs and higher throughput per hour when compared to a conventional single-row harvester. The data indicated that these units have a very significant advantage when harvesting low-yielding crops less than 80 t/ha when compared to a single-row machine.

PHOTOGRAPH 4: CORRADINI TWO-IN-ONE®

There are some significant constraints to the adoption of wide-swath harvesting. These include the lack of a factory-built production model 2-row machine, row-spacing configuration and associated issues, component specifications and set up, transport from field to factory, farming systems to suit wide-swath harvesting and industry acceptance, especially acceptance from growers.

John Deere are currently not manufacturing a double-row harvester for Australian row configurations (1.5 m, 1.8 m) because of the cost of manufacture. The factory production line produces one single-row harvester every 24 hours. Disruption to this product line when manufacturing a two-row harvester, which has a low market demand, increases the cost of production. However, this situation could change if there was sufficient demand for the product (N Toft 2008 pers comm.).

There are a number of machine component configuration issues because there is no standard row width across the industry.

Modifications to the gathering system may be required in wide-swath harvesting systems to ensure effective feeding of cane, while maintaining machine throughput.

A mismatch of the basecutter configuration (angle, number of disks) and the row-width configuration exists. This has posed issues in relation to cane pick up, cane loss, harvester driving, yield loss and, in some cases, ratoon failure.
As the delivery rate of the harvesters increases (as is wide-swath harvesting), the ability of the machine to clean the cane may lessen, particularly when harvesting green cane. Doug Young and Merv Greaves each operate double-row harvesters in green cane (in the Bundaberg area) and have had trouble in cane cleaning through their machines. Merv Greaves has developed and operated a double counter-acting vortex fan in the machine that he operates. It appears that this has addressed some of the issues associated with cane cleaning in such high-capacity, wide-swath harvesters. Opportunity exists to further monitor and assess this cleaning system, particularly in terms of cane loss (Di Bella et al. 2006).

Hockings et al. (2000) shows that, even with an optimum chopper system setup, cane and sugar losses are proportional to the throughput. Therefore, high pour rate translates into high losses. Therefore, there is the potential to increase cane losses through the cane-harvester chopper system in wide-swath harvesting.

There is currently limited data on the interaction of wide-swath harvesting on the cane transport system and the effect that it has on the entire value chain. The mismatch of harvester output and the mill transport ability causes inefficiencies in the current system. The introduction of wide-swath, high-delivery-rate harvesting may impact negatively on existing mill transport infrastructure.

There are a number of tools to analyse this scenario accurately and in detail. Higgins et al. (2006), Thorburn et al. (2006) have used modeling techniques to investigate whole-of-system optimisation. Further studies are required to model transport options with large-swath, high-capacity harvesting practices – this will involve rail infrastructure, road transport, trans-loading, delivery facilities (either rail transport, storage pads, truck transport), and cane haulage distances.

Dibella et al. (2006) identified that a lack of clear direction in row-spacing configuration is the major impediment to the large-scale manufacture of wide-swath harvesters for Australian conditions. For example John Deere is currently undertaking a production run of 20 2-row harvesters for the Brazilian configuration of 1.1 m.

2.2.3 Weight

The Australian ‘chopped cane’ sugarcane harvester is around 15,000 to 20,000 kg depending on make and model. For example the weight of a John Deere 3510 series harvester is 19,050 kg for a tracked machine and 15,420 kg of wheeled machine.

The average overseas sugarcane yield is about 80-100t/ha. Internationally, there would appear to be a significant market for smaller machines with an acceptable pour rate in these crops. Development of smaller machines is occurring both in China and India.

In areas of high labour costs (e.g. Australia), very high machine output is critical to reduce costs, but few overseas industries have these costs. The clear differentiation in machine requirements between Australia and overseas industries depends on labour costs and infrastructure to allow machines to deliver high pour rates. Therefore, in overseas industries multiple smaller machines are a better match.
Case IH is developing a small version of their 8000 series harvester as a potential solution to this issue. This is a lightweight chopper machine and is touted be marketed as the 4000 series.

2.2.4 Engine Size

The John Deere 3500 series harvester have an engine power output of 337 Hp (251 kW) at 2100 rpm (JD8061H 8.1L) with an option to increase power to 375 Hp. The Case IH 7000 series machines have an engine power output of 355 Hp (261 kW).

The high power availability and hence high fuel usage demand high productivity. This translates into high machine pour rates. In addition, high parasitic losses (e.g. cooling losses, component no load power consumption) reduce overall machine efficiency. Improved machine component-crop interaction (e.g. improved feeding) and minimising weight can reduce the need for high power requirements.

2.3 Summary

- Industry must move towards a controlled traffic system. Need to develop a system around this. Brazil is noted for low adoption of controlled traffic, primarily because of the influence of harvester manufacturers. For example, agronomically best yields are at 1-1.1 m, but must have 1.4-1.5 m as a compromise for Case IH and John Deere machines. However, there is a definite move to a 1.1 m controlled traffic system. Brazil is actively looking for harvesting strategies and solutions for this row spacing configuration.

- Increasing harvester productivity is essential to contain or reduce harvesting costs, wide-swath harvesting is one avenue that should be considered.

- Issues with fundamentals e.g. with current designs, billeting loses associated with increased pour rates.

- Industry needs to reach consensus on a uniform row spacing and standardise its row-spacing configuration

- Investigate further the options for wide–swath harvesting to contain harvesting costs. Within the context of machine design and throughput.

- The Industry needs to identify opportunities to achieve wider-swath harvesting under a controlled-traffic system i.e. limitations with Corradini Two-in-One® type systems.

- The industry should develop “systems-thinking” solutions and undertake value chain analysis on impact of wide-swath harvesting. e.g. impact on bin deliveries etc.
3 CROP HANDLING CRITERIA AND COMPONENTS

Figure 7 illustrates the layout and components of the Australian standard ‘chopped cane’ sugarcane harvester. The key components and areas in the harvester design layout that impact on the machine performance and have been the focus of research in recent years are discussed in the following sections.

3.1 Topper

Topping units have been in use in various forms even before the advent of mechanical harvesting and form an integral part in the supply of clean cane to the mill. With the progression to mechanical harvesting, the topping cutter was additionally required to gather in the leafy tops of the crop, cut them and direct the chopped material in a desired direction.

The progression to green cane harvesting and trash-blanketing system saw the development in the early 1990s of a new drum and of shredder-type toppers. During this period there has been considerable evolution and development in the concept. However, the fundamental problems with this arrangement have not been fully addressed. The disadvantages with this arrangement include poor gathering (inability to capture tops), shredding and poor directional control of the chopped material.

Currently, lodged cane cannot be topped; this results in higher EM levels through the harvester and mill, and a reduction in CCS and sugar quality. This is principally because the current toppers are not able to properly gather in misaligned or sprawled tops.
Tops in the cane supply can increase sugar colour, ash and starch levels by up to 10 times because they contain CCS-reducing compounds. Tops significantly impact on harvester capacity through increased levels of EM, which results in overloading of the choppers and cleaning systems.

For whole-of-crop harvesting if the approach is to preferentially remove tops and green leaf and retain these components in the field then the performance of the topper becomes paramount. The development and adoption of more erect ‘energy’ sugarcane varieties will also result in a significant focus on the performance of topping systems.

Whiteing (2002) has shown that the percentage of ‘cabbage’ in topped cane can be significant and contributes to higher EM levels. His field trials have shown that untopped cane yields approximately 4% greater tonnage than topped cane. However, despite this, increased tonnage net income to the grower was reduced by 5% due to the reduction in CCS. In the Tully mill area, the level of tops in the cane supply ranged from an average 4.6% in 1995 when crop conditions were favourable (standing) to 6.3% in 1998 when crop conditions allowed little topping to be carried out. This illustrates that even under good conditions when topping is carried out only an average of 30% of the tops are removed.

Presently, the harvester operator manually controls topping height. Subsequent feedback to the topper for differences in crop height along the row is erratic or even neglected. The majority of the time the operator cannot see the point of contact between the topper and the cane stalks from the cab. Even after the topping when the cane stalks are being fed into the harvester, there is too much waste material for any visual confirmation of the correct height of cut. Similarly a small change in basecutter height has a significant impact on topper height and manual adjustment is required.

Thus, there are significant advantages in automating the control of these processes to maximise the removal of leafy top and minimise the removal of millable stalk.

McCarthy et al. (2002) investigated processes of establishing an optimum topping height through the real-time measurement of the sugar concentration at the lowest point of contact between topper and cane stalk. A device that uses the chemical property of the cane stalk, and operates on similar principles to those in commercial refractometers to determine the correct cutting height was developed. This device, when coupled with a closed loop automated system to provide feedback and make fine adjustments independent of the operator offers, a potential solution in maintaining an optimum topping height. This system is still in the developmental stage and not commercially available to the industry.

3.1.1 Research Opportunities

In harvesting systems where the differentiation and removal of tops and green leaf is required an improved topping system will become paramount (dry leaf with cane, green leaf rejected). The development of a topping system which addresses the limitations of current designs should be encouraged. Design criteria should include:

- Improved gathering ability, shredding and directional control of chopped material
- Greater reach height and angle of approach to erect stalks.
3.2 Gathering System

The crop dividers are the principal component of the gathering system and have the function of aligning the material for presentation to the feed systems. They act by lifting and separating material from the next row and guide the cane into the front of the machine throat ready for butt-first feeding. A spiral wrap, comprising of an upward helix flight, is welded on to the crop dividers facilitate lifting of the cane. Hence, the crop dividers are commonly referred to as spirals. The industry standard gathering system comprises dual counter rotating spirals. The inner pair rotate towards the centre of the machine to gather and align the cane whilst the outer pair rotate outwards to separate cane from adjacent rows.

In crops that are particularly sprawled and tangled, operators use side trim knives (saws) that are fitted between the inner and outer spirals. The side trim knives prevent bridging of cane stalks between the spirals. The side trim knives may be lowered to cut the cane stalk in the centre of the interspace. They are an optional fitment on Case IH and John Deere factory machines.

Schembri and Garson (1996) investigated the mechanisms associated with harvesting heavy, lodged crops of green cane. The handling characteristics of green cane were different from those of burnt cane with the trash and top section of stalk binding the stalks and resisting the relative motion of stalks. Some difficulties were thought to be associated with uneven processing of cane. The problem seems greatest where the gathering system is required to significantly manipulate the cane in order to achieve the desired butt-first orientation. In extreme cases, the gathering system/feeding system of the harvester fails and the problem of ‘bulldozing’ occurs. Bulldozing can be defined as when the gathering system fails leading to gross pushing and carrying of cane ahead of the harvester.

Norris and Davis (1998b) identified and quantified several mechanisms involved in the gathering of heavy lodged crops of green cane utilising a combination of real time video and data acquisition systems. Deficiencies with the standard gathering system included:

- Dual counter-rotating spirals. In heavy crops, the counter-rotation of the outer spiral on each side reduced the ability of the inner spiral to gather and align cane because of cane bridging across the spirals.
- Geometry of spirals (i.e. diameter, length, taper and angle to crop relative to distance from the spiral to the basecutter). This allows a mismatch between spiral peripheral speed and the speed of the material moving across it.
- Bridging of cane stalks during initial gathering, and poor transfer of cane along the throat of the machine.
- The degree of unassisted feed between the first contact of the cane by the spirals and when positive feed is achieved by the forward feed components.

This work led to the development of a single-spiral gathering system (Norris and Davis 2001). The design of the system considered the design and layout of the gathering spiral. The angle of inclination, minor and major diameters, and pitch of the helix wrap of the gathering spiral were designed so that the surface speed of the spiral was greater than the speed at which the cane had to traverse the spiral to enter the machine as it moved forward. This was in contrast to the standard design where, because of its relatively large minor diameter and steep angle of attack, the spiral has a surface velocity higher than optimum near the ground. However, the spiral surface velocity is lower than the velocity at which the
cane traverses it, as the cane moves towards the top of the spiral, resulting in severe tension loadings on the crop stool and roots.

To assist the flow of cane, small rollers aligned in the plane of the knockdown roller and attached to the spiral frame were installed. The rollers operated independently of each other and in conjunction with each of their representative primary gathering spirals. The constraints of maximum pushdown angle as recommended by Kroes and Harris (1996) were considered in the design and positioning of these rollers.

To allow retrofitting to current- and old-model harvesters, a dedicated four-bar, non-parallel arm linkage was developed (Davis and Norris 2000). This linkage arrangement allowed the gathering system to operate without interference with the harvester mainframe and parallel with the ground irrespective of the harvester basecutter operating height.

Davis and Norris (2002) demonstrated that an incremental improvement could be made in the ability of harvesters to operate in heavy, lodged crops when fitted with a single-spiral gathering system. Improved feeding was quantified with more even loadings on machine components and the ability of the machine to harvest more lodged cane. This translated into improvements in machine performance with a 2% reduction in EM.

EHS manufacturing refined and commercialised the system and has sold in excess of 10 units in Australia and six units overseas (Ramu Sugar). This system is available built to order with a cost in the order of $A25-30K depending on fitments (S Lawn pers comm.). Commercial operators who have the single-spiral gathering system setup have reported benefits including; Improved flotation, visibility, gathering, feeding, higher cutting speeds and reduced chopper pressures. Observed improved ratooning over the standard gathering system in large crops was the primary reason for the importation of six sets by Ramu Sugar (CP Norris pers comm.). The market for these retrofit units has diminished with the development and fitment of single-spiral gathering systems to factory harvesters by Case IH and John Deere.

A similar single large-diameter spiral gathering system is standard on the 3500 series John Deere harvester. However, a second small side spiral and throat rollers (‘pig tails’) are optional (Photograph 5).
Case IH 7000 series harvesters also adopted a gathering system which incorporates crop dividers with a lower angle to the crop relative to the distance from the dividers to the basecutter.

The adoption of the large diameter single spiral concept by both manufacturers highlights the benefits being realised to the industry delivered through SRDC funded research.

### 3.2.1 Floating Sidewalls

Floating sidewalls pivot on the bottom of the crop dividers to follow the ground contour and assist in gathering stalks that have fallen into the interspace. There is anecdotal evidence to suggest that they grade significant amounts of soil into the basecutters and cane bundle. Manufacturers have designed slatted shoes to assist in dirt exclusion. They are a standard fitment on factory machines.

### 3.2.2 Height Control

The gathering system is connected to the harvester mainframe by two non-equal lengths, non-parallel linkage arms. A spring-loaded lift ram assembly enables some floatation of the system over varying ground conditions. A dynamically balanced linkage is required to control the height of the crop-dividers. The current crop divider linkage system tends to be dynamically unstable, hence control is difficult. Massey Ferguson and Mizzi machines had a dynamically stable linkage.

The crop divider height setting is crucial in reducing the amount of lost cane during gathering and reducing the level of soil intake. Improper adjustment of the crop divider height during harvesting affects both the quality of cane supplied to the mill and the gathering efficiency.
The proportion of dirt entering sugar mills has tended to increase since the introduction of mechanical harvesting (Garson 1992). Ridge and Dick (1992) identified that the ploughing action of crop divider shoes contributed to high levels of soil in cane. Kent et al. (1999) showed that during the raw-sugar refining process CCS is degraded in proportion to the percentage of dirt in the harvested cane.

The operator can manually control the height of each crop divider. Attempts at developing means of automatically sensing or controlling the crop divider height on harvesters have occurred in recent years. The approaches can be classified into two classes, the mechanical contact and the non-contact sensor.

**Mechanical-Contact Sensors**

The mechanical contact type sensor measures the ground height using a skid or wheel. The main problems with this type of sensor is the interference from trash, mud and/or cane itself in that it is often caught in the device causing jamming of the mechanical movement.

Lawrence and Bigg (1996) highlighted the use of three crop-divider modifications aimed at improving crop divider shoe height setting in the Innisfail region. One method was the installation of solid wheels mounted behind the crop divider shoe. The wheel supported the weight of the crop divider assembly, and was set at a height that the crop divider shoe just skimmed the ground surface. Secondly a large point was fitted to the crop divider shoe; this allowed the shoe to be operated well above the ground surface, with the large point ensuring that any lodged cane was gathered.

Thirdly an innovation that provided feedback on crop divider height was the attachment of small hydraulic rams to the crop divider lift rams. These small rams govern the oil height in a gauge mounted in the harvester cabin and are similar to the gauge used for base cutter height. In wet soil, if the crop dividers sink down into the soil, this system can provide instant feedback to the operator. These innovations can be installed at minor cost $A<500.

**Non-Contact Sensors**

This type of sensor attempts to determine the ground position by detecting changes in an electromagnetic field or a travelling wave that interacts with the ground.

Schembri (2000) investigated the use of ultrasonic sensors to detect the ground surface. These sensors transmit an ultrasonic signal that measures the delay in a sound wave that is reflected by the ground. Schembri et al. (2000) developed a system for controlling basecutter height based on ultrasonic sensors. This system was extended for use in controlling the crop divider height.

The system incorporated an ultrasonic sensor positioned behind the crop-divider shoe. The sensor provided ground-height measurements; these measurements were relayed to a commercial Programmable Logic Controller (PLC). The PLC operated the electric solenoid for the crop divider lift ram, so as to maintain a set height above the ground for the crop-divider shoe. A minor modification to the shoe design was required to ensure that all trash was prevented from passing beneath the ultrasonic sensor beam, given that trash would cause incorrect ground-height measurements. The crop divider height-control system has
been field tested and performed satisfactorily. However, no measurements comparing the system with manual controls were reported.

Case IH Austoft to date has not commercialised the automatic crop divider height-control system. Hence, it is not currently available as a retrofit system or on standard factory fitment.

3.2.3 Side Trim Knives

Side trim knives are mounted on the outside of the inner spiral (between inner and outer spiral) and operated as required to eliminate any bridge locking over the spirals which occurs in green cane harvesting.

For whole-of-crop harvesting in two-year-old crops in NSW, these are essential because of the nature of the crop to lock into the next row with the length of the stalk and knotting of the leafy tops. There have been a number of novel industry-led approaches in the development of saws.

Photograph 6 (Left) shows pair of side trim knives developed for whole-of-crop harvesting in NSW. The configuration incorporates a disc with 8 attached basecutter blades. The disc rotates at about 1600rpm. Whilst providing an adequate solution for trimming material, the potential for cane and sugar losses during operation is significant as shown by the sugar shower in Photograph 6 (Right) during operation in burnt cane conditions.

PHOTOGRAPH 6: WHOLE-OF-CROP HARVESTING CROP DIVIDER SIDE TRIM KNIVES (LEFT) AND SIDE TRIM KNIFE OPERATION (RIGHT)

3.2.4 Benefits Delivered

- A fundamental understanding of the machine-crop interactions in particular the principles and concepts associated with gathering and aligning lodged and sprawled green crops. This has raised awareness of the issues involved in these processes.

- Development of an alternative gathering system for cane harvesters. Developed to a commercial product and provided an impetus for manufacturers to adopt alternative gathering systems on later model machines.
• A number of methods for automatically sensing and controlling the height of crop dividers have been developed. The lack of commercialisation of these products has been driven by market demand and the perceived increase in capital cost of machines.

• Simple systems such as ‘trainer wheels’ are effective in enhancing height control.

• Alternative designs which are dynamically stable have been developed and dramatically enhance height control without additional hardware.

• Market demand in Australia for improved products (e.g. gathering system, height control) is driven by harvester operators who wear the full cost of this improvement and receive no direct benefit from improved cane supply quality and reduced losses.

• An example of an industry-led solution are the modified side trim knives developed for improving the ability of a harvester to harvest whole-of-crop two-year-old cane in NSW.

3.2.5 Research Opportunities

The crop divider height setting is crucial in reducing the amount of lost cane during gathering and reducing the level of soil intake. The current linkage system tends to be dynamically unstable. An industry-led, simple, cost-effective solution (dynamically stable) for controlling the height of the crop-dividers should be encouraged.

• The impact of alternative component designs (e.g. modified saws) on harvesting losses should be quantified.

3.3 Forward Feeding

Davis and Norris (2000) demonstrated that current harvester designs cannot effectively harvest unburnt, heavily lodged crops. Under these conditions, the machine/cane interactions produce inconsistent flows of cane through the harvester, that is, instead of a uniform flow rate, the cane is processed in peak-starve pulses. These pulses in the cane flow increase stool damage as material is bulldozed in front of the machine, overload the machine components as gluts are processed, reduce the performance of the choppers and exceed the capacity of the cleaning systems. This results in an overall reduction in machine capacity and performance.

Davis and Norris (2000) identified and quantified the impact of the forward-feeding components (knockdown roller, finned roller, basecutters and buttlifter) on the flow of material through the machine and the components’ ability to actively control and feed cane.

The development and subsequent testing of a harvester for high-density plantings has illustrated the level of feeding achievable with modifications to the forward-feeding zone (Norris and Davis 2001). However, there is still a fundamental lack of understanding of the interactions occurring between the machine components and the cane in the forward-feeding zone of current harvester designs. In this zone, understanding the relationships between the knockdown roller, finned roller, basecutters and buttlifter is paramount to addressing issues
such as minimum knockdown angle to achieve reliable butt-first feed, control of cane after severing by the basecutters, and the lifting into and the stratification of material up the feed train. Addressing these issues is vital to allow for increases in current machine performance and for the development of improved machine designs.

Davis and Norris (2003) developed a novel approach to investigate and quantify the interactions occurring between the machine components and the cane in the forward-feeding zone. An existing harvester was modified to allow alternative forward-feeding systems to be set up and tested under identical conditions. Modifications to the front end allowed incorporation of any forward-feeding layout by fitting a choice of modules. Two modules were developed, which incorporated the standard leg gearbox and underslung gearbox basecutter configurations respectively. Section 3.4 describes these two basecutter configurations. Each module, when installed, allows the harvester to be operated as a fully functional harvester.

This approach has been adopted by EHS manufacturing, Mackay who has modified a number of standard machines for alternate farming systems applications.

The flexibility of the modular format enables enhanced forward-feeding geometries to be evaluated and quantified using identical harvester extractor/chopper/extractor setups. Importantly, these modules can be fully evaluated in the field under commercial conditions.

Instrumentation, including high-speed cine film and data acquisition of loadings on components to characterise the flow of cane, was utilised. Comparative trials under varying crop conditions determined the flow of cane through the leg basecutter and underslung basecutter modules. Resulting high-speed cine film showed contrasting feeding patterns between the two modules.

To complement the investigations undertaken by Davis and Norris (2002a) on the machine components/cane interactions, a finite-element model was developed of the forward-feeding zone (Schembri 2002). The model included the knockdown roller, finned roller, basecutters and entry to feed train. This model was used to evaluate alternative design layouts on feeding ability (Davis and Schembri 2004).

Whiteing and Kinston (2008) assessed the impacts of machine design and operating parameters on stool damage, subsequent ratooning rates and final yields over a crop cycle. They compared a standard forward feeding geometry with an enhanced forward feeding module with zero knockdown.

**Underslung basecutter module**

Davis and Norris (2002a) reported that this setup was characterised by a consistent flow of material. Stalks were orientated in the direction of travel and in two distinct streams. The majority of stalks were aligned between the centre and the outer edge of both basecutter discs, with a smaller number of stalks flowing over the centre of the gearbox. Layering of material was evident with stalks and tops on top and trash underneath, and the depth of material was even and consistent throughout. Baulking of stalks was evident with those stalks entering across the centre of the gearbox. The impact of the buttliffter and chopper system could be seen, with stalks pulsating at the respective frequency of the buttliffter slats and engagement of the chopper knives.
The interaction between the fins on the finned roller and cane was evident, with the fins actively maintaining alignment of stalks. Additionally, the finned roller controls the depth of cane via its location in the forward-feeding layout.

Davis (2002) designed and developed an alternative forward-feeding module based on the underslung basecutter arrangement. Davis and Schembri (2004) found that the alternative forward-feeding geometry resulted in a more even flow of cane based on pressure loadings on components and a reduction in trash and roots and dirt when compared to the standard feeding geometries.

*Leg basecutter module*

Davis and Norris (2002a) reported this setup was characterised by the agitated flow of material. The depth of material over the basecutters was increased due to a lack of constraint by the finned roller. The alignment of stalks was disorderly with the majority of stalks moving across the basecutters at an angle of approximately 45°. Few stalks were presented to the buttlifter parallel with the direction of travel and more frequent stalk baulking was evident than in the underslung module. A plausible explanation is that the butts of the stalks are impacting the first top feed roller due to the depth of material.

From the analysis of the high-speed data, the finned roller has a significant impact on the flow of material into the feed train.

The key elements and design criteria of the forward-feeding zone in order of layout are now discussed.

#### 3.3.1 Knockdown Roller

Knocking down the cane is important to achieve reliable butt-first presentation to the machine. The angle of knockdown is an important consideration in minimising damage to the stool before the basecutters start to cut it. Kroes and Harris (1994) evaluated the severity of knockdown damage and failure modes of stalks and stools in an experimental rig. This allowed the development of a classification system, which shows how the severity of damage responded to knockdown parameters. Results indicated that decreasing the knockdown angle to zero eliminated stool shattering and major damage to the stool in the form of major splitting was found at a 20° knockdown angle.

Kroes and Harris (1996) demonstrated that knockdown damage was caused when brittle stalks snap off prior to being cut, stools are loosened, stalks are shattered on impact, and ‘spring back’ of the cut stalks occurs, giving the appearance of high base cut which is in fact not so. They found that the ultimate strain of cane in bending is approximately 1.8% and independent of stalk diameter and variety. They defined 15% failure curves for 20, 30 and 35 mm diameter stalks (Figure 8). These represent the maximum deflection at a given height of knockdown where no more than 15% of the stalks are prone to breakage.

Although the knockdown roller can be lifted on current model harvesters, the adjustment is not high enough to clear the 15% failure curve with large diameter stalks. It is clear from the failure curves that most stalks will be broken or suffer bending damage with the current positions of the finned and knockdown roller (Figure 8). The belief that the knockdown angle is dictated by the position of the knockdown roller on current industry standard machines is
incorrect and it is the position of the finned roller that is the limiting factor. The degree of knockdown caused by the finned roller causes considerable damage to standing cane stalks and the cane stool being harvested as illustrated by Kroes (1997). In firm soil, the knockdown and finned feed rollers in current harvesters will break and collapse the majority of stalks before the basecutters reach them. For some varieties, this type of failure will result in large splits to the base of each stalk, and cause the billet to separate into two or more fragments (Kroes 1997). Field trials found that losses through the extractor system due to excessive knockdown angles may be as high as 7.5%.

![Diagram of cane failure curves and location of forward feeding components](image)

**FIGURE 8: CANE FAILURE CURVES AND LOCATION OF FORWARD FEEDING COMPONENTS (KROES AND HARRIS 1996)**

Whiteing and Kinston (2008) found that ground loss and pickup loss were reduced by up to 50% with the enhanced forward feeding module.

### 3.3.2 Finned Roller

The finned roller assists in the feeding of material before severing with the basecutters. Once the cane has been severed by the basecutters it is necessary that the stalks be controlled as soon as practical, otherwise the now cut and loose bundle will travel ahead with the machine in ever increasing quantities.

A certain amount of ram effect takes place due to the inertia of the mass relative to the machine. This effect must be exploited further by ensuring a good grip on the cane bundle. This can be achieved by use of a floating feed roller, so that all stalks are gripped between the basecutter discs and the floating roller.

The forward-feed roller is critical to the feed performance of the harvester. The position of this feed roller was determined by Davis (2002) from the relationships of minimum knockdown-angle strain curves and basecutter discs/buttlifter positions. This roller must provide an aggressive feed element after the cane is cut by the basecutters. Davis (2002)
achieved aggressive feeding capability by designing the roller to float so that all volumes of cane are gripped between the basecutter discs and the buttlifter.

Davis (2002) determined the feed-roller diameter by the average trash/leaf length to prevent wrapping. The peripheral speed is matched with the remaining feed rollers. The feed roller is of open-slat design to minimise weight. It pivots from the front, allowing the rotational kinematics of the roller to be utilised in aiding floatation.

The alternative forward-feeding module was field trialled in 2002 with the positive feed engagement being the standout characteristic of its performance. The extended stub rollers provided a minimum knockdown angle and essentially the stalks were very close to erect when severed by the basecutters. This minimal angle posed no limitation to the feeding ability. After severing by the basecutters, stalks commenced to feed via the combined action of the forward feed roller and buttlifter (Davis 2003). The performance of the alternative forward-feeding module was quantified in Northern NSW where crops in the order of 200 t/ha were harvested.

Machine performance data was collected with a 1.5% reduction in EM levels recorded with the alternative forward-feeding module when compared with the standard leg basecutter module. In addition, the results indicated that the percentage roots and dirt in the cane supply was greater when harvesting with the standard leg basecutter module than when harvesting with the enhanced forward-feeding module. In both setups the cutting depth was identical. This result highlighted the fundamental differences between the gathering and feeding characteristics of the modules.

3.3.3 Benefits Delivered

- A fundamental understanding of the machine-crop interactions in particular the principles and concepts associated with feeding and basecutting of sugarcane. This has raised awareness of the issues involved during these processes.

- Alternative forward-feeding geometries. Quantified improved feeding in large green crops. Design concepts embodied in designs of machines modified for new farming systems.

- Demonstrated the concept of zero knockdown whilst still providing effective butt-first feeding of cane.

3.3.4 Research Opportunities

There are fundamental knowledge gaps in machine forward-feeding performance with respect to whole-of-crop harvesting and green cane harvesting at current industry pour rate levels. These include:

- The impact of volumetric capacity and feeding efficiency when harvesting for high biomass systems (whole-of-crop, high pour rate).

- The concept of zero knockdown and the impact of knockdown on stool damage and sugar losses should be further explored.
3.4 Basecutters

The basecutters sever the cane stalk at or below ground level and assist in feeding the stalk, butt-first, into the feed train. The basecutting process interacts with the soil, the stool and the harvested stalk.

Two types of basecutters exist, underslung and leg-box basecutters. Underslung basecutters drive each disc via a gearbox mounted under the disc. The gearbox has reduced reliability and can be subject to stalling in wet conditions due to friction between the discs and the gearbox. Underslung basecutters are no longer available as an option from the harvester manufacturers as a fitment to factory machines. All late model harvesters are fitted with leg-box basecutters. In leg-box basecutters, both basecutter discs are driven from above through legs attached to a gearbox. Basecutter blades are timed through the gearbox to pass under the adjacent disc. High-speed photography of the forward feeding zone by Davis and Norris (2003) has demonstrated that the standard underslung basecutting arrangement produces a more even flow of cane through the machine when compared with a standard leg-box basecutter.

Kroes and Harris (1994) evaluated the severity of damage and failure modes of stalks and stools in an experimental rig. This allowed the development of a classification system, which shows how the severity of damage responded to basecutter parameters. Henkel et al. (1979), Ridge and Dick (1988), Garson (1992), Ridge and Linedale (1997), Kroes (1997), DaCuhna Mello and Harris (2000), Crook et al. (1999) and Davis and Norris (2001) have identified cultural, operational and design features as affecting soil levels in the cane supply and basecutter interaction with the crop in an attempt to quantify the level of damage and juice loss occurring in the base cutting process. The individual components include are explained below.

3.4.1 Basecutter Angle

Basecutters are angled forward (12-18° for leg basecutters and 18-30° for underslung basecutters) to facilitate butt-first feeding and to minimise dragging of the discs or gearboxes on the cut stubble. The angle is either manually or hydraulically adjustable.

Ridge and Dick (1992) identified both cultural factors and harvester operational features as affecting soil intake by harvesters. Industry extension surveys by Linedale and Ridge (1996) targeted basecutter-angle setting as having potential for reducing soil in cane. Ridge and Linedale (1997) assessed the impact of basecutter angle setting and row profile on the soil in the cane supply. Trials indicated a significant reduction of soil in cane when the basecutter angle setting was matched to the particular row profile. In the situation where a flat basecutter angle was matched with a high hill height, as opposed to a flat hill height, an increase of 0.75% soil in cane was measured. Similarly, a steep basecutter angle was matched with a low hill height, as opposed to a high hill height, an increase of 0.7% soil in cane was measured. The reasons hypothesised for this are, that in flat row profiles, the basecutter geometry indicates that if cane is cut effectively at ground level, a steep basecutter angle will cause the basecutter to dig in on either side of the row. In hilled row profiles harvested with a flat basecutter angle, it is necessary to cut deeper in order to gather...
cane growing from the side of the hill. Therefore, soil levels can be reduced significantly by adjusting the basecutter angle to match the row profile.

3.4.2 Basecutter Speed

On the majority of industry-standard harvesters, the basecutters rotate at a fixed rotational speed. The forward speed at which modern harvesters are able to harvest current crop sizes have increased concurrently with the increase in available engine power. Kroes and Harris (1994) found that a major cause of damage to the cane is contact between the basecutter disk and the stalk prior to the completion of the cut. Cane damage due to disk contact is attributed to excessive harvester ground speeds or feed rates. Current harvesters probably cause damage at normal field speeds (Kroes and Harris 1994).

Kroes and Harris (1995) investigated the quality of cut as affected by a number of basecutter parameters, including incline angle, speed, knockdown angle, feed rate, blade shape, and lateral cane position. The severity of damage and modes of failure were classified and sensitivity analysis undertaken on the various parameters. They found that the knockdown angle, basecutter speed and feedrate had a high impact on the severity of damage. The apparent correlation between the feed rate and the number of damaged stalks led to the development of a model by Kroes and Harris (1995) that describes the basecutter kinematics. The model calculates the maximum permissible velocity ratio (feedrate/disk rotational speed) to maintain total blade coverage of the cane crop and to prevent contact between the disks and uncut stalks for a given basecutter and crop parameters. In addition, the model can be used to investigate the effects of variation in the crop parameters on the maximum permissible forward speed of the harvester. Figure 9 illustrates the maximum permissible forward speed in a sandy soil. Within one working day the maximum forward speed has been reduced to virtually zero.

For a given ground speed, an overly high basecutter rpm will result in stool being cut by the blades multiple times. When the basecutter rotational speed is too slow for the forward speed, then a tearing cut results and stalks are torn off by the disc before a blade reaches the stalk; this causes severe damage to the stool.

The blade length and number of blades per disk have the greatest impact on the maximum permissible forward speed (Kroes and Harris 1995).
Kroes (1996) found that the minimum permissible impact speed required to successfully complete a cut with acceptable damage is dependent on the variety of the crop harvested. For high fibre, an impact speed of 17 m/s was required and 14 m/s sufficient to cut low fibre varieties. Figure 10 illustrates the impact speeds and maximum permissible forward speed for five-blade basecutter disks with 3 blade length scenarios (40 mm extension, 75 mm extension and full blade extension. This shows that at a basecutter speed of 600 rpm the harvester is restricted to about 11.6 km/hr to avoid disk contact. The permissible speed drops sharply with blade wear. The majority of industry machines would be operating at or above the permissible forward speeds. Limiting the harvester forward speed to the green zone will eliminate damage and subsequent loss due to partial cuts. These low forward speeds, however, are not considered practical.
3.4.3 Basecutter Disks

Basecutter discs are constructed from solid pressed steel. The thickness of disk is typically in the order of 16 mm with the blades fixed to the underside of the disk. Five- or six-bladed disks are available.

Ridge and Dick (1992) evaluated the performance of soil rejection by the basecutter disk itself through the use of scalloped disk designs. Limited trials were undertaken, with the results illustrating an average 1.5% reduction in dirt at the mill from the scalloped disks. Scalloped disks did not receive a favourable acceptance by from the industry and there are currently none in use.

Ridge and Linedale (1997) evaluated the effect of 5° dished basecutters on soil levels. They found in some trials that dished disks significantly reduced soil levels by 0.15%, but additional trials proved inconclusive.

Dished disks and disks with holes in them are marketed by after-market manufacturers and are claimed to reduce the level of dirt in the cane supply. They are priced similar to standard solid basecutter discs. There is only anecdotal evidence and no quantifiable data to support this.
3.4.4 Basecutter Blades

Conventional double-disk basecutters use rectangular blades, which cut the cane using a direct-impact cut.

**Blade Thickness**

Blades are available in 4 mm, 5 mm and 6 mm thicknesses and may also be hardfaced. Kroes and Harris (1994) demonstrated in an experimental rig with variety Q124 that the blade thickness showed little difference on the quality of cut.

**Blade Wear**

Basecutter blades require regular adjustment and replacement due to wear. Blade wear and associated downtime costs the industry an estimated $1 million per year (Spinaze and Subramanian 1999). Operational conditions with abrasive soils influence the degree of wear and/or soils with high rock levels may bend or break blades increasing operating costs and downtime.

Kroes and Harris (1994) found that as blade wear increases (manifested as a reduction in blade length) cutting is affected and damage to the stool and stalk can occur. Kingston et al. (2002) utilised the damage classification system developed by Kroes and Harris (1994) to investigate the impact of basecutter blade condition (square edged v rounded but little reduction in blade length) and post-harvest application of soil drench fungicides on any interaction with ratooning under different trash management regimes. The results illustrated that blade condition had no significant effect on stool damage and that a high percentage of the stool damage was associated with the partial cuts arising from the knockdown angle. No significant effects on ratooning were detected from square edged or rounded basecutter blades. The work by Whiteing and Kinston (2008) found that field variation had a greater influence on stool damage than basecutter setup and blade condition.

Reducing basecutter blade wear is one approach to improve the economic efficiency of harvesting by reducing downtime and blade costs. Spinaze and Subramanian (1999) undertook a rigorous testing programme aimed at improving the overall performance of basecutter blades through the application of surface engineering technology (hardfacing). Only limited experimental data was gathered, but blades with 20 mm wide and 3 mm thick edging of tungsten carbide and cobalt along the top and cutting edge were the most cost-effective product.

**Blade Shape and Angle**

The conventional rectangular basecutter blade cuts the cane using an impact cut. Kroes and Harris (1995) investigated the kinematics of the basecutter configuration and illustrated that the relative velocity of the blade during impact is essentially perpendicular to the cane surface. This direct impact cut damages the cut cane and imposes high forces on the stool (Kroes and Harris 1995).
Harris and DaCunha Mello (1999) considered alternative basecutter blade geometries that cut the cane by a combination of slicing and direct cuts, and that are aimed at reducing cutting forces and cane damage. They extended the Kroes and Harris (1995) kinematic model to include consideration of the cutting process in terms of the relative velocity of the blade during impact. They analysed a range of alternative curved blade edges. The results illustrate that two cutting edge geometries, including backward and forward facing blades, offer more appropriate opportunity than standard blade configurations for controlling the magnitude and direction of edge velocities and, thus, the direction of the force on the stalks.

Harris and DaCunha Mello (1999) also investigated the microshape of the cutting edge to facilitate proper functioning of the curved blades. Various configurations of serrations on the slicing edge of the blade were evaluated. Further investigation by DaCunha Mello and Harris (2000) of the cutting ability of serrated edges compared with straight and curved smooth edges was undertaken in an experimental test facility. Under these conditions, the results indicated that juice loss from standard blades is in the order of 280 kg/ha, whilst juice lost from serrated blades is only 200 kg/ha. A damage classification system similar to that used by Kroes (1997) illustrated that serrated edges cause less damage than standard blades. In-field testing of curved and serrated blades, there was a 13% reduction in stool disturbance and lower dirt intake over standard blades. This translated into a higher number of ratoon shoots of five shoots per metre versus three per metre, and a reduction in CCS of 0.7 units and a reduction in EM of 1.5% at the mill when compared with conventional blades (DaCunha Mello and Harris 2001).

However, these trials were undertaken with the serrated and curved blades cutting above the soil surface, whilst the standard blades were cutting at the soil surface. The validity and resulting comparisons drawn between these treatments are, therefore, questionable.

### 3.4.5 Benefits Delivered

- A fundamental understanding of the machine-crop interactions in particular the principles and concepts associated with cutting of sugarcane. This has raised awareness of the issues involved in this process.

- This has led to enhanced knowledge and quantified losses and damage in these processes (e.g. knockdown, basecutting).

- These have underpinned HBP guidelines in particular farming for harvesting (row profile) and harvester setup (blade length, optimum forward speeds).

### 3.4.6 Research Opportunities

- There is a fundamental knowledge gap with respect to the forward attitude of the basecutters to the ground. That is, what is the optimum blade angle and the effect of changing blade angle on quality of cut, losses and dirt in the cane supply.

- Alternative concepts for cutting of sugarcane.

- An education process for farming for harvesting with respect to row profile and ‘fill-in’ should be an industry priority.
3.5 Feed Train

The function of the feed train is to accept cane as it is being severed by the basecutters and deliver it to the chopper system in a consistent manner. Case IH 7000 and John Deere 3500 series harvesters have a 11 or 10 roller feed train respectively which consists of two layers of powered rollers, one above. The rollers in the top layer are free floating to allow for variations in cane swath thickness and the bottom-layer rollers are fixed. The top and bottom layers of rollers rotate in opposing directions, effectively pulling the cane swath through. The feed train rollers are hydraulically driven in most harvesters and their speed of rotation can be fixed or varied (Norris et al. 1999). The first bottom roller in the feed train is termed the buttlifter roller and is mounted behind the basecutters and guides cane, butt first, into the remaining feed rollers.

In an attempt to maximise the potential for the harvester feed train to reject dirt, rock and stones, whilst giving variable feed to the choppers to manipulate billet length, Case IH 7000/7700 and Cameco 2500 series machines run a feed train set-up where:

(a) The lower group of bottom feed-train rollers rotate at a low average tip speed in an attempt to maximise time for rejection to occur, whilst the matching top rollers run at higher speeds, to enhance agitation of the cane bundle and enhance feed. Typically, the feed train is separated into two roller groups running at different speeds. The first four rollers are typically set to a speed of either 100 or 135 rpm with the last six rollers running between 100-200 rpm;

(b) The upper roller group (i.e. the six rollers closest to the chopper system) is variable in speed.

The most significant issue relating to this machine set-up is that the length of a typical stalk of cane is greater than the length of the harvester feed train. Therefore, the cane stalk is simultaneously subjected to a range of different roller speeds, which is not conducive to even feeding of material.

Whilst adjustment of feed train speed is available to change billet length, limited research had been undertaken of the impact of billet-length distribution, billet damage on cane and juice loss. Norris et al. (1998b) demonstrated that significant damage to cane stalks, including splitting and crushing is occurring in the feed train before the cane is billeted.

There is anecdotal evidence to suggest that the variation in roller speeds helps even out the flow of cane through the machine by separating bundles and gluts. Research by Davis and Norris (2002) demonstrated that the standard feed train roller setup further deteriorated the evenness of feed through the harvester and impacted on machine performance. The uneven flow of material was exacerbated between the first floating feed train roller and the last floating feed train roller before the chopper system.

Davis and Norris (2002) found from the analysis of feed train roller displacements of the first and last top feed rollers that the phase shift recorded between their displacements is greater than what the relative positions of the rollers could account for and that the displacement pattern of the last feed train roller does not closely follow the pattern of the first top feed train.
roller. The combination of these two events demonstrated that differential separation of stalks is occurring in the cane bundle between these two rollers during processing.

Ridge and Dick (1992) investigated feed train design through the use of an experimental test facility, which replicated a harvester feed train. This test facility allowed testing of benefits from changing roller speed and type of roller to be evaluated on soil rejection. Trials were undertaken to evaluate the effect of different roller types, roller speeds and top roller pressures on soil rejection. The major factors that improved soil rejection were reduced rotational speed of the buttroller roller and spring loading of the top floating rollers to increase pressure on stools of cane (Ridge and Dick 1992). Recommended speeds for buttroller rollers and pressure loadings have not been determined.

Fundamental work by Norris et al. (2000) on the relationships between feed train parameters and chopper systems was undertaken using a full-scale chopper test rig. The test rig is a fully functional stationary replicate of the industry-standard harvester feed train and chopper system and is shown in Photograph 7. The test rig facility was instrumented to allow measurement of hydraulic pressure, feed train roller displacement and rotational speed. This allowed detailed analysis of power consumption and the effect of feed train roller speed on evenness of feed and billet quality parameters (Hockings et al. 2000).

Extensive test rig trials were undertaken to assess the impact of the standard feed train roller speed setup on evenness of feed, billet length, billet-length distribution and cane/juice loss.

Initial trials with the chopper test rig demonstrated that, where all feed train rollers operated at the same speed, the evenness of feed was dramatically improved compared with the standard harvester feed train. Results also indicated that the average of all roller speeds has greater influence on cane feed-rate than the speed of individual roller groups. The variation in speed of the upper group of rollers is, therefore, less effective at controlling billet length than was previously thought.

The results from the test rig were extended to field trials where the feed train of a standard research harvester was modified to allow all feed train rollers to operate at the same...
rotational speed (except the buttroller). The hydraulic plumbing on this harvester also allowed the feed train roller speeds to be returned to their original setup for comparative purposes. Davis and Norris (2002) investigated the effect of synchronised feed train on dirt levels. They measured a reduction in soil levels of 0.3% when the feed train was synchronised.

Synchronising feed train rollers involves setting the surface speed of all the feed train rollers to the same speed. This involves minor modifications to the chopper/feed train hydraulic circuit. Depending on the original circuit, modifications may include, changing oil flow to the chopper motors, chopper motor sizes and or feed train roller motor sizes.

BSES Ltd have assessed the feed train and chopper setup of more than 100 harvesters throughout the industry from 2002 as part of an ongoing feed train and chopper optimisation service (BSES Ltd 2008). A large percentage of these optimisations have been on machines used for cutting plant material as there are a number of billet length/density issues with respect to commercial machines.

The feed train on the John Deere 3500 series machines is configured such that all rollers operate at the same nominal surface speed. However, this speed can be reduced by bleeding off oil through a pressure-compensated flow control valve.

### 3.5.1 Roller Design

The standard Case IH 7000 series harvester’s feed train comprises 11 feed rollers, six bottom and five top floating rollers. The John Deere CH3500 series harvesters comprise 10 feed rollers. The Case IH 7000 series harvesters have a typical roller design incorporating the top and the three last bottom feed rollers with 200 mm nominal pipe diameter with six or eight slats of open teeth fixed to the outer diameter. The first bottom roller (buttroller) and the next two comprise a solid 50 mm shaft with either three or four open-teeth slats attached to the centre shaft. The John Deere CH3500 series harvesters have a typical roller design incorporating the top and the four last bottom feed rollers with 250 mm nominal diameter.

Ridge and Dick (1992) investigated roller design on dirt levels in their feed train test facility. Roller designs included finned top and bottom rollers and three- and four-bladed slat rollers. Minor improvements in dirt rejection were obtained with finned top and bottom rollers that were designed to break up cane stools, and with three- or four-bladed bottom rollers throughout the harvester feed train. Field evaluation of modified roller designs were carried out under dry conditions, with only minor improvements in soil rejection compared with standard rollers (Ridge and Dick 1992). No documented evidence of the results and roller designs were given.

After-market harvester component manufacturers produce a wide range of alternative roller designs (e.g. Corradini (2008), Trail Bros (2006), NQAS (2008)). The majority of these designs have evolved from grower/contractor innovations and have not undergone rigorous evaluation or had performance quantified. These include:

**Spiral rollers:** The move to leg basecutter gearboxes in the early 1990s offered enhanced functionality and reliability over the original underslung design. The restriction placed on the material as it moved between the legs caused a concentration of material in the centre of the feed train. This resulted in localised wearing of rollers and chopper blades. Spiral rollers were invented to spread the concentrated material after the basecutters in the feed train to
present a wider, thinner layer of cane to the choppers. No quantifiable data exists on their performance.

**Buttlifter design:** The buttlifter roller is mounted behind the basecutters and guides cane, butt first, into the feed train. Research by Massey Ferguson (MF RandD Design Notes) and Ridge and Dick (1992) have shown that the buttlifter design and operation are critical to the rejection and/or entrapment of dirt in the cane supply. The design of the buttlifter in production machines is of solid three- or four-bladed slat design. Manufacturers have investigated the use of open buttlifters to reduce the amount of dirt entering the cane supply. No documented evidence is available on the effectiveness of this system.

Three-or four-bladed open buttlifter designs are available to the industry through after market manufacturers of harvester components marketed to reduce dirt. Similarly no documented evidence is available on the effectiveness of these types of designs.

### 3.5.2 Benefits Delivered

- A fundamental understanding of the machine-crop interactions in particular the impact of the feed train system on feeding and billeting of sugarcane.

- Quantified the losses associated with standard feed train/chopper system relationships at the industry pour rates at that time.

- Developed optimum feed train setup guidelines and implemented modifications to over 100 harvesters throughout the industry.

- Provided the science to and the impetus for the manufacturers to change feed train setup on later model machines. This has significantly improved the performance of these machines.

### 3.5.3 Research Opportunities

- The fundamental research on feed train configurations and losses were undertaken in the late 1990’s using technology and operational settings in use at that time. In recent years, the industry has moved to higher machine pour rates than in the late 1990’s due to machine productivity issues and there has been some changes to the feed train layout of later model machines. The impact of current industry pour rates on feed train configurations with a particular emphasis on resulting damage and sucrose losses is a priority.

- An understanding of the losses associated with these newer machines could be gained from research undertaken overseas e.g. Argentina.
3.6 Billeting System

The billeting system (chopper box) is required to chop a cane stalk and trash mat, up to 250mm thick into lengths generally between 150 mm and 250 mm. Since the adoption of chopper harvesters, a number of different billeting systems have been employed, varying from the swinging knife, single-drum, chop-throw to the rotary-pinch system.

The swinging knife concept incorporates a rotating vertical baseplate with its axis perpendicular to the cane feed. The baseplate has a single or dual blades attached to its periphery similar to a lawnmower. The drum rotates and the cane is severed against an anvil. This billeting system was in use by the Toft range of machines until the 1980’s. There is no known published data on the performance of the swinging knife type chopper systems.

One advantage of the swinging knife is that the cutting action is independent of the feed train, therefore in theory an infinite range of billet lengths can be determined.

The single-drum chopper consists of a drum with tangentially mounted blades which glance past a fixed blade (or cutting bar) in a guillotine action. This cutting method appears to be more efficient and precise than the pinch/scissor action of the conventional rotary-pinch chopper system with radial blades.

A single-drum chopper has been previously used commercially in the sugar industry by the Mizzi ‘Scorpion’ harvester, built by Walkers Limited. The unit was used in the 1980’s and early 1990’s before being replaced with a rotary-pinch chopper system. Poor feeding ability, regular knife breakage and knife sharpening requirements have been given as the main reasons for its demise. Apparently there were always major problems with "glut-starve" feed due to poor "layout" of the forward feed components of the machine. This would have seriously contributed to issues such as knife breakage. Also the knives were poorly supported and an automatic knife sharpening system did not exist (Lamb et al. 2008).

The chop-throw concept as a key component in cane harvesters has been under investigation for over thirty years but has not, as yet, had a major impact on the development of commercial cane harvesters. Many of the claims for the system have not been realised (Norris, 2000).

The original concept was developed by Cannavan (Inkerman Mill Suppliers 2002) in the 1960’s. Bonel developed a chop-throw harvester based on the same concept in the mid 1990’s. Cannavan’s chop-throw harvester and the Bonel Machine are shown in Photograph 8. The Bonel machine was a light weight conventional single row chopper harvester and the gathering and feeding components followed industry standard layout and design. The fundamental difference in the machine was the utilisation of a chop-throw mechanism in place of the conventional system of rotary pinch chop and elevator.
The chop-throw mechanism incorporates a rotary cutter with a knife blade on a rotating shaft and a thrower having a vane extending from the thrower shaft. The two shafts are parallel and contra-rotated. The cutter knife blade and vane co-acting to sever cane fed into the chopping cutter into billets. The thrower vane acting to throw the severed billets upwardly through a cane guide chute from which they are deposited on a transverse conveyor to the haulout (Cannavan U.S. Pat. No. 4,295,325).

The Bonel chop-throw had a thrower diameter of 1.2 m and rotational speed of approximately 127 rpm giving the billets a velocity of approximately 8 m/sec, in a near vertical trajectory through the cleaning chamber (Figure 11).

**Figure 11: Schematic side view of the Bonel prototype chop-throw harvester (Norris 2000)**
Norris (2000) identified from high-speed photography of the cutting mechanism that there was significant visible juice loss as billets were cut and thrown and suggested that this could be a major issue for the industry if the concept was commercialised. This was supported by the relatively low billet quality ratings of around 16-22%. However, the magnitude of the chopping losses were not quantified.

The commercial development of chop-throw machines has ceased due to limited availability of finance for refining the chop-throw system, and the cleaning system. However, the concept has recently found some renewed interest with grower group innovation funding from SRDC and successful funding to develop a new generation double row chop-throw machine. A dual chop-throw chopper system has been developed and is currently awaiting the completion of the new generation double row harvester for testing (Cannavan 2007).

The rotary pinch-chop concept for the billeting of cane was originally developed in the 1950s by engineers at Massey Ferguson, for incorporation in the MF515 chopper harvester (MF RandD Design Notes - U.S. Pat. Nos. 3,788,048 and 3,830,046). It has been in universal use from the early 1980s. During this period, however, there has been considerable evolution and development in the concept, along with a degree of ‘recycling’ of concepts (Norris et al. 1999).

Rotary-pinch chopping systems consist of two machined contra-rotating drums with hardened steel replaceable blades mounted parallel to the axis of the drums so as to pinch and sever material passing between the drums. On current machines, the drums are hydraulically driven by two individual motors and are synchronised by timing gears. A flywheel running on a separate shaft driven by the top timing gear gives added inertia to reduce the pulsing that would occur if additional energy was not available during the chopping process. The flywheel is fitted with a slip clutch to protect the gears from overload in the event of a solid object being passed through the blades.

The current design of rotary-pinch chopper systems incorporate two, three, four or five blades per drum equi-spaced around the circumference at 180, 120, 90 and 72 degrees respectively. Thus, during 1 revolution of the drum, two, three, four or five billets are produced all of equal length (in the case of a synchronised setup) depending on the blade configuration.

The original rotary-pinch chopper system was developed as an over-centre chop concept, where interacting blades or blade anvil arrangements completed their engagement as they aligned between the centreline of the choppers. An alternative approach was the hoe chop, where the chopper blades complete the cut well before they align between the centreline of the choppers. This design essentially superseded the over-centre chop as it offered lower power consumption, lower cut losses, lower juice losses and lower billet damage. The concept had been taken to the extreme in the design of the Massey Ferguson 405 prototype in the early 1980s with high-speed cine and advanced logging techniques being used to optimise the design (Norris et al. 1999).

With the exhaustion of Massey Ferguson patents on the concept, the Versatile Toft 7000/7700 (and later the Cameco CH2500) adopted the rotary-pinch chopper system in their harvesters. These designs were based on the original MF515 design. It was a hoe-chop design with chopper drums of 12-inch centre spacing (as the original 515 had been).

This remained the industry standard design, despite significant increases in machine throughput throughout the period. Perceived problems with this design led to the
development of alternative designs by after-market harvester component manufacturers such as Westhill Manufacturing and Trail Bros Manufacturing, with a range of other alternative designs being developed by innovative farmers.

The 12-inch chopper system remained in use until the mid 1990s. The dramatic increase in material processing rate was further exacerbated by the significant reduction in bulk density caused by harvesting crops green rather than burnt before harvest (Schembri and Garson 1996).

By the mid 1990s, the chopper system was clearly a major constraint on machine performance, following increases in installed engine power from 180 to 230 kW (240 to 310 horsepower). The manufacturers and after-market suppliers at that time were seeking solutions, both for retro-fitting to machines in the field and for fitting as original equipment.

After limited field trials in 1995, Case IH and Cameco introduced choppers of 15-inch centres into their machines in 1996. Both designs appeared to reduce power consumption at high pour rates, effectively increasing machine capacity. However, both manufacturers encountered billet quality as a major problem in many mill areas in their 1996-model machines.

An additional entry to the market during 1996 was a chopper utilising unequal drum diameters, the differential chopper system. This gave a blade entry configuration initially approximating a blade/anvil configuration, changing to a hoe chop as the cutting cycle progressed.

The differential chop has become the preferred system because, as the blades wear, billet quality does not deteriorate as quickly when compared to a standard over-centre chop. The differential configuration incorporates a slightly smaller diameter lower drum. Because of this, the blades wipe over each other and will bed-in. That is, the top blade will wear a seat into the bottom blade as it wipes pass repeatedly. Cutting takes places on this seat, rather than on the ends of the blade. This means that the quality of the cut will not decrease as rapidly as the blade edges wear and become damaged. In a rotary-pinch chopper system, cutting occurs on the edge of the blade. For this reason, billet quality quickly diminishes as the blade edge wears and becomes damaged.

The move from 12-inch to 15-inch choppers highlighted the issues of chopper performance including billet quality and billet length distribution. Norris et al (1999) investigated the actual operation of the rotary pinch chopper system.

The chopper test rig facility developed by Norris et al (2000) allowed the performance of different chopper system designs to be characterised and their optimum operating conditions determined. Chopper system modules were developed to incorporate both 12-inch and 15-inch systems. The test facility allowed:

- The relationships between cane feed train nominal velocity, chopper peripheral velocity, billet length, billet length distribution and billet quality of each chopper at different pour rates to be quantified. Power consumption and instantaneous torque loadings were also assessed.
- The inherent juice and fibre losses and billet damage in the cutting process with the different designs and under different harvesting conditions to be quantified, i.e. feed rate, billet length and cane type.
• The impact of wear and poor adjustment on chopper system performance to be quantified.

Norris et al. (1999) and Hockings et al (2000) undertook a comprehensive test program with harvester and chopper system manufacturers to evaluate the performance of five different commercial chopper systems (and one non-commercial system) under differing cane variety characteristics, at different processing (pour) rates and at different feed-train roller speeds (billet-length settings). The results of this test program:

• Illustrated the magnitude of losses associated with the billeting process. Losses were in the order of 2-3% at 120 t/hr and 4-5% at a 240 t/hr pour rate for a billet length of 300 mm.

• Demonstrated that manipulation of feed-train speed to control billet length adversely impacts on billet length distribution, reduced quality and losses.

• Demonstrated that the energy consumption during billeting is low compared to the peak loadings of 125 kW experienced by choppers in machines. Typical mean power consumption at 240 t/hr is about 15 kW. The dramatic difference in average power consumption and installed power in harvesters is to allow compensation for the magnitude of the glut-feed events that occur during harvesting.

• Quantified that the forces induced in the cane bundle are of very significant magnitude, resulting in cyclic acceleration and deceleration of the cane bundle and the feed train rollers. Forces range from minimal when the tip speed of the chopper blades were 65% feed train speed to greater than 18 kN when feed train speed was 30%. This is equivalent to the drawbar pull of a 90 kW tractor.

• Showed that billet quality whether sound, damaged or mutilated is extremely dependent on initial cane characteristics, pour rate and relative peripheral speed of the feed train rollers and the choppers. Billet damage measured with brittle varieties were in the order of 45% and this compares with damage levels of 30% when harvesting tougher varieties.

• Illustrated that a doubling of feed train roller speed gives an average increase in mean billet length of about 33%.

• Losses from billeting with sharp blades ranged from 2 to 5% and up to 9% with blunt blades.

The results indicated that cane and juice losses could be decreased and billet quality improved through best-management techniques. This is achieved by harvesting less brittle varieties at lower pour rates, with matched peripheral speeds of the feed train rollers and choppers, and by ensuring that the blades of the chopper system are maintained in a sharp condition.

The results of research by Norris et al. (1999) quantified that losses up to 9% can occur in the billeting process and that machine design and operation can significantly impact on the magnitude of these losses. The results also strongly indicate that field losses may be of greater magnitude than indicated in this testing program.
The most appropriate way to quantify billeting losses is in percentage loss per cut per metre (% loss/cut/metre). That is, a 330 mm billet has 3 cuts per metre, whereas a 100 mm billet has 10 cuts per metre.

The percentage loss per cut per metre (%/cut/m) will range from:

- a minimum of 0.6% for new blades, pour rate < 120 t/hr and billet length > 2 nodes,
- greater than 1.5 % for high pour rates “average” blades and shorter billet lengths.

Chopper systems with large numbers of blades can be expected to have even higher losses per cut per metre, particularly at higher pour rates.

The greatest impact on rotary pinch chopper performance in terms of minimising losses and improving billet quality is not the blade configuration or size of chopper unit but the operating parameters. These include the crop condition, pour rate and the feed train roller peripheral speed and chopper peripheral speed relationship (Norris et al. 1999).

Davis (2005) further investigated the issue of uniform billet length and resultant lower bin density associated with feed train/chopper optimisation. There is limited data on the impact of billet length distribution on transport capacity. However, it is known that with the improved billet length distribution from synchronised machines, the transport system is penalised with lower bin densities by approximately 10%.

The approach to this issue involved the development of a novel modified rotary pinch chopper system. The novel approach was to obtain varying billet length during one revolution of the chopper drum not through varying the mismatch in chopper/feed train speed ratio as in the current harvester setup. This issue was based on the premise that non-uniform particle sizes translates into a high packing density, thus higher bin weight Davis (2005).

Proof-of-concept trials found that the variable length billets treatment produced the highest packing density and the uniform length billets the lowest packing density. This translates into a reduction of 8.1% in bin weight from variable length billets. The packing density and bin weight of a combination of variable and uniform length billets was also assessed and found to reduce the bin weight by 4.8% from variable length billets Davis (2006).

Davis (2007) developed a conceptual design for a modified rotary-pinch chopper system. The design incorporated a blade geometry such that nominal billet lengths from the ‘variable’ drum of 295 mm; 295 mm; 205 mm could be attained. Corradini Engineering of Ingham undertook the detailed design and manufactured a proof-of-concept modified 15-inch rotary-pinch chopper system.

Trials found that the ‘Standard’ chopper variable billet length treatment resulted in the greatest packing density, with 380 kg/m³ and the uniform length billets the lowest with 365 kg/m³. Packing density was translated into a weight for a nominal 6t railway bin for direct comparison. Theoretically, an average reduction in bin weight from variable to uniform length billets was calculated to be 4%.

The packing density of the ‘Corradini’ proof-of-concept chopper uniform length billet treatment was found to be 375 kg/m³, which is greater than the standard chopper uniform length billets, but less than the standard chopper variable length billets. The corresponding
average reduction in bin weight from the standard chopper variable length billets was found to be 1%. Alternatively, an average increase in bin weight of 2.4% was found when compared with the standard chopper uniform length billets.

During this work, the industry moved to four blades per drum chopper systems, therefore effectively rendering three blade chopper systems obsolete for commercial applications.

Davis (2007) highlighted that there is a distinct lack of interest in reducing sugar losses during harvesting at both the sugar industry and harvesting sectors’. Contributing to the situation is the current harvest payment system which provides no incentives for the harvesting sector to minimise sugar losses during harvest. The resultant reduction in bin weight translates into increased transport costs which are a direct disadvantage to the harvesting sector. This issue will be discussed further in Section 5.2.3.

Whilst, Norris et al. (1999) and Hockings et al. (2000) gained a understanding of the interaction between the feed train and rotary-pinch chopper system through high-speed cine and physical measurements and quantified the losses associated with billeting of cane, there is little published data on the behaviour of a stalk and the mechanisms present during the cutting process at a fundamental level.

EHS manufacturing has developed a rotary-pinch chopper system with 12 blades per drum (Photograph 9) to reduce billet length and improve the bulk density of material in whole-of-crop harvesting in NSW. The system produces a 75 mm billet (S Lawn 3009 pers comm.) and underwent initial trials in NSW in November 2008. No performance data is available for this system.

PHOTOGRAPH 9: EHS MANUFACTURING PROTOTYPE 12 BLADE ROTARY-PINCH CHOPPER DRUM

Barnes et al. (2008) investigated single knife slicing of sugarcane stalks against a stationary anvil in an attempt to gain a better fundamental understanding of the knife-stalk interaction. This knowledge was then applied to the design/modification of a harvester billeting system in an attempt to reduce stalk damage and losses. They identified that the angle between the knife and stalk, depth of cane matt, blade condition (sharp v blunt), trash level and variety as major factors in mass loss.
Lamb et al. (2008) investigated alternative billeting systems in an attempt to address loss and billet length issues associated with the rotary pinch system. The billet length from a rotary-pinch chopper system is basically fixed by the number of blades per drum. Variations in billet length are only possible by changing the speed of the feed train relative to the chopper speed. This leads to a sub-optimal feed train/chopper relationship, inefficient chopping action and therefore increased sugar loss.

The single-drum chopper concept, in use in forage type harvesters was evaluated as a potential solution to these problems. The difference between the proposed single drum chopper design and previous designs (Walker Mizzi) is the ability to keep blades sharp at all times by incorporation of self-sharpening technology developed for forage harvesters (Lamb et al 2008).

Lamb et al (2008) compared the potential cutting behaviour of a single drum chopper with that of a conventional two-drum chopper using a 2-dimensional analysis of the rotary-pinch system and three-dimensional kinematic modelling of the single-drum chopper system. Modelling showed that minimum drum speed was critical to ensure that the product would be ejected cleanly without recycling.

A full-scale (but partial width) single-drum chopper was developed and a test rig built to evaluate performance, optimise the design and set-up. Blade sharpness and thickness were found to be of paramount importance, but also significant are angle of cut, thickness of mat and, to a lesser extent, knife speed.

Further work is still required to fully optimise the cutting process, develop a commercial prototype for retro-fitting to a commercial machine and undertake field evaluation. The practicality and capability of this system to handle foreign material in the cane matt (e.g. rocks, timber etc) also needs to be assessed.

The development of billeting systems that can deliver low loss whilst producing billet lengths suitable for a range of harvesting scenarios (e.g. green cane/whole-of-crop) is of increasing importance. The harvesting sector in NSW, has seen the need to chop shorter billets in order to increase the payload of cane that can be loaded into in-field and road transport bins with the advent of 5 blades per drum (175 mm billet) and 6 blades per drum (145 mm billet) rotary-pinch chopper systems being used in the last couple of years. A 12-blade per drum rotary-pinch chopper system has been developed and was evaluated in New South Wales in December 2008 (S Lawn 2009 pers comm.).
3.6.1 Benefits Delivered

- Quantified the performance of rotary-pinch chopping systems available to the industry at that time under controlled conditions. Benefits to industry have been through understanding the feed train/chopper drum relationships to minimise cane and juice losses. This work underpinned the HBP guidelines for chopper setup and operation.

- Demonstrated that high pour rates lead to high losses even at optimum setup.

- Field losses from the rotary-pinch chopper system are expected to be higher than those measured under controlled test rig conditions.

- Highlighted that the billeting system is an area of high loss. Hence initiated a program of research investigating alternative chopper designs to minimise sucrose losses and overcome limitations re billet length distribution for improved bulk density.

3.6.2 Research Opportunities

The billeting system is an area of high cane and sucrose loss. The industry should be actively pursuing solutions to address this issue. An investigation of the fundamental chopping process should be a priority and include:

- Assessing both contact and non-contact concepts which reduce on the percent loss per cut per metre.

- Assessment of chopper systems with large numbers of blades which can be expected to have even higher losses per cut per metre, particularly at higher pour rates.

- Environmental considerations from the impact of sugar juice entering waterways causing de-oxygenation may drive the development of a low loss per cut billeting system.

3.7 Primary Cleaning System

Considerable resources have being committed by funding bodies to projects addressing more appropriate cleaning chamber designs and alternative cleaning system concepts. To achieve the full potential offered by any of these advanced concepts, a major redesign of the harvester is necessary and, as such, this is a medium to long-term development by the manufacturers. Therefore, the research effort has been expended on the manipulation of the concepts within the constraints of the current harvester layout.

The primary cleaning system on standard harvesters is an extractor type system. It has a three or four-bladed extractor fan contained within an enclosed cleaning chamber and a directional discharge hood that sits on top of the cleaning chamber to direct trash away from transport and other areas. The fan is very similar to the familiar ceiling fan which had a small hub relative to its diameter, and the flat steel blades simply formed into a circular cross
section shape. The fan can be mounted on a cantilever arm (horizontal arm) or underslung (vertical arm) on an arm extending down from the top of the hood. The vertical arm is the usual mounting system, has better cleaning efficiency, and has been in widespread use since 1994.

The extractor type cleaning system is a crude, inefficient but physically robust system when compared to other materials-handling separation systems. Billets are ejected into the confined cleaning chamber at approximately 45° from the chopper system, but in diverging trajectories due to the expansion of the cane matt as it leaves the choppers. Air is drawn upwards through the falling billets to remove trash; the trash is subsequently ejected through the extractor fan with the air. Two factors impact on the performance of this type of cleaning system:

(a) Non uniformity of the vertical airstream means that whilst air velocities induced in some parts of the cleaning chamber are sufficiently high to draw cane into the extractor, in other areas the velocity is lower than that required for effective cleaning (Figure 12). Ridge and Pearce (1996) measured velocities in the cleaning chamber close to the fan of 10-20 m/s. In addition to this variability, considerable turbulence from high levels of swirl induced by the fan was also recorded up to 40 m/s.

(b) To prevent cane on the upper trajectories from the choppers being immediately drawn into the fan, a deflector plate is used to, at the least, confine the upper limits of the flow, but more typically divert the mean trajectory of the billets downwards. Trials by Whiteing (2002) measured a increase in cane loss of 5% when deflector plates are not installed.

The extractor type cleaning system has a number of advantages over alternative concepts. These include:

- Cane entry trajectory is of little importance
- Allows a compact machine layout
- Simple design and easy to fabricate
- Direct material easily to where required
- Destroys the evidence of cane loss, therefore cane loss is not an issue.
The current extractor type cleaning systems do not achieve both high extraneous matter removal and low cane loss at the high pour rates the industry now demands. Cane loss from harvesters operating in factory setup of over 15 t/ha were measured by replicated mass-balance trials (as distinct from blue tarp tests) by Whiteing and Norris (2001). The inadequacies in the design of current cleaning systems for high pour rate cleaning are exacerbated by inappropriate presentation of the cane to the cleaning chamber directly from the choppers (Hobson 1995). Hobson (1995) found that reducing billet rotation at the chopper would significantly improve separation efficiency. A billet stream greater than a single layer thick emerging from the chopper was found to produce highly variable separation efficiencies.

Considerable resources have being committed by SRDC to projects addressing more appropriate cleaning-chamber designs and alternative cleaning-system concepts. To achieve the full potential offered by any of these advanced concepts, a major redesign of the harvester is necessary. This can only occur over a medium- to long-term time-frame.

The presentation of material to these systems (directly from the choppers) is such that the potential of the concepts is unlikely to be fully realised. If, however, more area at the rear of the harvester was available, better designs exploiting more of the potential performance gains of these concepts would be possible.

There have been a number of attempts to improve the cleaning efficiency in the primary cleaning chamber by modelling techniques, modifications to its geometry, fan design and by reducing fan speed. This work has been undertaken within the constraints of the current harvester layout.

3.7.1 Hood Designs

Early hood designs were simplistic, easy to fabricate from steel and formed an inverted L-shape over the cleaning chamber. The material flow patterns of this design cause extreme localised wear. With steel hoods, wear areas are simply plated when the steel wears through.

The availability, price, weight and field maintenance advantages of plastic hoods have made these the preferred type since the mid 1990s. Plastic hoods have replaceable plastic liners to overcome wear problems.

Ridge and Dick (1988) assessed harvesters modified for green cane harvesting and found that cleaning could be improved and cane losses decreased by altering fan mounting positions and modifying the design of the extractor chamber. Ridge and Pearce (1996) investigated the development of a more efficient primary cleaning chamber and hood design.

Evaluation of existing commercial and semi-commercial cleaning systems showed that the cleaning performance of a vertical arm extractor was superior to a horizontal arm extractor and efficiency was affected by factors such as deflector plate angle and blade tip clearance. Cane losses reduced from 16.3% to 12.7% and EM from 7.5 to 6.9% when using the vertical arm extractor instead of a horizontal arm extractor.

Ridge and Pearce (1996) undertook an extensive analysis of air-flow velocities and direction within a standard extraction chamber. This led to the development of a new prototype hood
using aerodynamic principles to minimise pressure drop at the outlet and improve uniformity of air velocities in the cleaning chamber. The prototype hood, in the shape of a lobster, was fabricated from steel. From this steel hood a polyethylene mould was developed to facilitate manufacture of the tapered and smoothed shape from plastic. A plastic hood was manufactured and tested. Trials of a range of cleaning chamber configurations and inlet vent positions were carried out and a cleaning system was developed that incorporated a plastic hood with extended steel barrel, additional air vent in the rear of the extractor and a widened base on the air inlet cone.

Field testing of this system showed an increase in air velocities from 13.1 to 17.2 m/s at a fan speed of 1100 rpm. The inclusion of an rear vent directing air flow against the flow of cane from the chopper reduced cane loss by 44% and EM by 1.2%.

Ridge and Pearce (1996) demonstrated significant improvements in performance of extraction system through modification of the cleaning chamber to enhance airflow. With relatively minor modifications to inlets, they demonstrated that airflow patterns could be improved and separation of trash from billets improved. Increasing the height of the fan above the trajectory of the billets was also shown to improve cleaning. Redesigning the hood allowed more efficient fan operation and a more-even velocity profile to be induced across the fan face, reducing areas of high velocity airflow.

The design of the lobster hood was suitable as a replacement on Austoft and Cameco harvesters, but commercial use of this system was limited because the extended barrel was too high for road transport. Transport height of harvesters is a real consideration and the overall height of the system presented considerable logistic and practical problems for machine transport.

Although manufacturers did not adopt the lobster hood, they took on board a number of fundamental concepts embodied in its design, including chamber design and extended barrels.

### 3.7.2 Modelling of Primary Cleaning Chamber

The development of harvester cleaning systems has undergone significant refinement. However, there is little engineering science to underpin the design process (Hobson 1997).

The cleaning system is nearly always a pneumatic system (Joyce and Edwards 1994). Air is readily available and non-polluting, and aerodynamic differences exist between the particles to be accepted (billets) and the particles to be rejected (leaf, tops). Joyce and Edwards (1994) focused on the separation of cane billets from trash by studying the aerodynamic properties of the particles in the cane supply. A model incorporating experimentally determined aerodynamic characteristics of cane particles was developed. This model was used to predict the trajectories of the cane components in a pneumatic cleaning system.

This model was based on a dilute-phase assumption, in that there is no interaction between the particles. The model was used to predict the effects of varying air velocities, feed velocities, and injection angles on the size and power requirements of a pneumatic cleaning system. The limitation with any dilute-phase model is that it is restricted to predicting the operation of lightly loaded systems with insignificant particle collisions.
Hobson (1995) extended this work by investigating the effects of separation process of particle-particle interactions in heavily loaded systems. A single-impact model was developed that enabled the prediction of two essential pieces of information, the duration of contact between two colliding billet or leaf particles, and the mean force exerted by one particle on another during the impact (Hobson 1995). Further work enabled the development of a multiple-particle model to allow investigation of pneumatic separation efficiency over a wide range of pour rates and particle characteristics.

Hobson (1997) validated the model in a wind tunnel and used it to investigate the performance of high-pour-rate extractor-type cleaning systems. The results indicated that the greatest potential for system improvement lies in controlling the motion of particles as they emerge from the chopper into the extraction chamber. The model predicted that an intermediate mechanical means of control, such as a conveyor between the chopper and the cleaning chamber, would reduce particle spin, maintain a constant launch velocity and frequency, and ensure a thin cane stream is presented to the air flow. This would result in similar performance characteristics in cane loss and EM levels at a pour rate of 150 t/hr, which would exceed a standard system operating at 90 t/hr (Hobson 1997).

Hobson (1997) also suggested that the full benefits of improvements in the way cane is delivered to the extraction chamber are unlikely to be fully realised until modifications are also made to improve the uniformity of flow through the cane stream.

3.7.3 Current Designs

Recent developments in primary cleaning chambers have included increases in cleaning chamber diameter up to 1.5 m (5ft) (John Deere 3500 series), modifications to entry and exit, and mechanical reliability design points. The primary cleaning chamber on Case IH 7000/7700 have remained at 1.28m (4.2 ft) diameter.

PHOTOGRAPH 10: JOHN DEERE 3510 (5 FT) PRIMARY EXTRACTOR FAN

Note the orientation of the deflectors around the perimeter of the cleaning barrel in Photograph 10 (Left). Their orientation will act to direct material into the fan, as shown by the wear pattern Photograph 10 (Right), hence, increasing the potential for cane loss.
Anti-vortex System

The Anti-vortex system was designed by NCEA and Case Austoft to improve the airflow in the primary extractor chamber (Zillman and Harris 2001). Extractor type fan designs induce airflow in the extractor chamber which swirls and is not of uniform velocity. The ideal airflow is purely axial in direction, and uniform in velocity across the entire fan area.

Zillman and Harris (2001) revised standard methods for the design of axial flow fans, to allow the required radial distribution of lift coefficient to reduce inlet swirl and improve blade life in a new fan design.

The production model, known as the Anti-vortex fan differs from a conventional fan in that it has a hub that extends to half of the fan diameter and four relatively short but broad blades formed to a circular arc in cross section, but also twisted along their length. The design method assumes that this hub is covered by a centre body or nose cone so that the airflow into the blades is axial. The nose cone is constructed from the same plastic as extractor hoods. It looks very different from traditional extractor type fans.

Zillman and Harris (2001) reported no comparative performance data from their new fan design.

Case IH (2008) report that the operating speed of the Anti-vortex fan can be reduced from 1300 rpm to 850 rpm when compared with standard fan designs. The design reduces the vortex effect while reducing cane losses by up to 50%. The operating power requirement is reduced by approx 30 Hp (22.4 kW), with positive benefits on fuel consumption.

Case IH claim that the operating at 850 rpm, the Anti-vortex system reduces the percentage of trash (leaves and stem) by around 20% compared to other systems. In addition, cane losses are reduced by 70% (Case IH 2008).

The Anti-vortex fan is standard on all Case IH Austoft 7000 Series production harvesters built from 2003. It is also available as a retrofit option for older machines.

PHOTOGRAPH 11: ANTI-VORTEX FAN
Data on the performance of Anti-vortex fans are available from overseas industries. These data are from machines fitted with Anti-vortex fans and without and where sampling cane quality is undertaken on scheduled basis. This has indicated that the cleaning performance of machines with Anti-vortex fans is a poor correlation with manufacturer’s performance data. Therefore, this confirms the need for independent testing.

3.7.4 Counter Rotating Fans

The uniformity of the vertical airflow impacts on the performance of the cleaning system. High levels of swirl induced by the fan adds to this variability and causes considerable turbulence (Ridge and Pearce 1996).

To improve the uniformity of the airflow and reduce the degree of swirl, a novel concept was developed by Eric Archibald a grower/contractor in north Queensland. In this approach, a second extractor fan is mounted below the existing extractor fan. The lower extractor fan rotates in the opposite direction. Both fans draw air up, but the swirl effect of each fan is opposing and cancels out the swirl. Limited testing of the system showed that, compared to a standard system, near-infrared (NIR) fibre was reduced from 15 to 14% and NIR ash reduced from 1.85% to 1.49% when the counter-rotating fans were used. Case IH Austoft acquired the rights to commercialise this system, however no production units were developed.

3.7.5 Alternative Cleaning System Designs

Blowers

There are a number of disadvantages with the extractor type cleaning system. These include:

- Rapid blade wear due to trash and dirt which is exacerbated in green cane
- Fan jamming due to mud build up.
- Substantial billet loss through the extractor
- High power consumption
- Severe swirl in the cleaning chamber
- Performance drops dramatically with worn fan blades.

Massey Ferguson recognised these limitations and incorporated into their MF405 preproduction prototype a cross axial blower cleaning system. These designs enabled large volumes of air supplied by two opposed axial flow fans at low horsepower to be directed into the cleaning chamber.

The blower cleaning system design has a number of advantages including:

- Overall blade wear is eliminated
- Reduction in 75% of the horsepower because of higher aerodynamic efficiency when compared with extractor type systems.
- Reduction in billet loss due to laminar air flow and reduction in swirl.
Therefore, a well designed blower cleaning system to produce laminar airflow into the cleaning chamber has a number of potential benefits and should be further investigated.

**Chop-Throw**

From an engineering perspective, the chop-throw concept appears to have one outstanding advantage for the separation of materials on a cane harvester, which has not been exploited by the industry. That is the velocity (including directional control) and presentation of billets leaving the thrower (Norris 2000).

Norris (2000) undertook dilute and dense phase modelling of separation of cane components along with high speed photography of the chopper and cleaning system to evaluate the potential for the design of an effective cleaning system for chop-throw harvesters.

Norris (2000) found that cane loss was generally minimised, and leaf removal maximised where a narrow high velocity air stream rather than a wider, low velocity air stream was used. Billet loss became unacceptably high where the fan axis was located above 2 m. Cane loss was minimised by introducing the air stream below a height of 1 m.

Norris (2000) indicated that a system injecting billets into the cleaning air stream at a higher velocity than conventional harvesters, such as the chop-throw gives greater potential for effective cleaning without significant cane loss.

**Jet Clean**

Zillman and Harris (2001) investigated the concept of combining high-speed narrow jets with a low-speed general flow to separate and then extract the trash and dirt from the cane flow. The system is installed behind the chopper on an extension of the standard harvester elevator slew table and uses a combination of high-speed air jets, which agitate and separate the cane flow and a low speed flow that removes the separated trash and dirt through the extractor fan. The secondary extractor fan has been eliminated. Billets are not removed by the narrow jets, but the trash is ejected very effectively. This was demonstrated in an experimental rig and then the system was implemented on a harvester.

This combination of airflows cleaned with very low cane losses and almost complete removal of EM. Zillman and Harris (2001) claimed that cane loss and EM were no longer coupled as in the conventional chamber.

A small number of row for row comparative trials with a standard harvester with 12-inch rotary-pinch chopper system were undertaken. The blue tarp method with no fan speed loss factor was used to assess cane loss. This was based on the premise that the normal factors used do not apply when using the NCEA four bladed fan because the billets don't appear to be as fragmented as with the standard fan.

Zillman and Harris (2001) reported an EM level of 2% compared with 4 % from a standard machine. From the same trial the ‘Jet Clean’ cane loss was reported as 0.73 t/ha compared with 0.98 t/ha from a standard machine.

Field trials highlighted a number of issues with this approach including its performance in wet weather and the impact of 12-inch rotary-pinch versus 15-inch rotary-pinch chopper systems on its performance. Whilst, it is claimed the ‘Jet Clean’ displayed simultaneous low billet loss...
and low extraneous matter levels when used in conjunction with a 12-inch rotary-pinching chopping system, the higher velocity of the projected billets from a 15-inch rotary-pinching chopper system made the billets prone to extraction by the fan.

Due to the limitations in its functionality of design, performance with 15-inch rotary-pinching chopper systems and reliability problems in the wet, the system was not commercialised.

3.7.6 Benefits Delivered

- Research on cleaning system design has been undertaken within the constraints of the current harvester layout and has shown that a major harvester redesign is required for major advances.

- Current designs have been optimised with an understanding of the impacts of fan speed on cane loss.

- Products such as the Anti-vortex fan design are a commercial solution which has been adopted by manufacturers.

3.7.7 Research Opportunities

The cleaning system is an area for potential high cane loss and warrants further consideration. Specific areas of investment include:

- Independent assessment of the losses from alternative component designs and later model machines (e.g. Anti-vortex fan, 5 foot cleaning chambers). This should be a priority for the industry and to provide quantifiable data for whole-of-system modelling scenarios.

- An understanding of the losses associated with these newer machines could be gained from research undertaken overseas e.g. Argentina.

- Alternative concepts (e.g. blowers) have demonstrated the potential for minimising cane loss. Depending on the direction of the machine purpose (e.g. green cane v whole-of-crop) other components may be a priority.

3.8 Elevator

The function of the elevator is to lift the billeted cane from the base of the primary extractor fan and deliver it into a haulout. Elevators swing from side to side to allow delivery on either side. Kits are available to extend the length of the elevator when harvesting in dual rows or other specific row configurations.

The standard harvester elevator consists of a truss and a pressed metal frame containing a chain and flight conveying system. The elevator is an S-shape structure, nominally 850 mm wide, and supports a chain and slat system operating over a stationary, typically perforated floor to convey the product. The weight of the standard elevator, and the position of the
centre of gravity when harvesting means that the support structures must be strong and, therefore, heavy. However, increased weight of the machine, particularly around the rear axle, makes the machine more stable. The elevator can rotate through 160° in the horizontal plane (slew) to enable the harvester to cut a one-face operation. Additionally, the height of the elevator is adjustable to provide high clearance for haulout vehicles. It can be lowered to allow clearance from overhead obstacles during travel and for maintenance.

Whilst harvester manufacturers aim to minimise elevator mass, its mass and the mass of the secondary extractor not only add to machine weight, but also adversely impact on machine stability when operating across slopes. Alternative elevator designs have been researched.

Harvester manufacturer CNH Austoft investigated the reduction of harvester weight and found that a major constraint was the weight of the elevator (M Baker, pers comm.). Its weight and weight distribution dictated the required strength and overall weight of the machine, if acceptable stability and durability were to be achieved. The research concluded that, if a lighter weight elevator with reduced overturning moment were achievable, further weight reductions in other components of the harvester would be possible (M Baker, pers comm.)

Previous attempts to redesign the elevator from non-ferrous metals (e.g. Aluminium) to reduce weight have introduced seemingly insurmountable problems with wear, electrolysis/corrosion, durability and cost. The future design of elevator frames may comprise fibre composite materials.

3.8.1 High-speed Elevator

Davis (2002) investigated the development of a lightweight elevator and advanced secondary cleaning system. The concepts embodied in the project followed on from those developed by Norris and Davis (2001), and the potential to transfer high-speed conveyor technology from other industries.

The development of the system targeted enhanced machine performance through reduced cane loss, lower EM, and higher pour rates, whilst reducing machine weight and improving machine stability.

The elevator design used a high-speed hugger belt system, fed from an elevator bowl developed to feed the hugger belts. The elevator bowl design offers enhanced airflow, as well as fewer space constraints on the design of the primary extractor and blower type secondary cleaning module. A proof-of-concept prototype system was developed and tested in the field. The lighter weight, and more importantly lower overturning moment of the elevator assembly was an advantage with machine operators. The prototype was designed as both a retrofit item and for fitting to new machines.

However, major operational and reliability problems were encountered in the testing of the prototype system. The major difficulty encountered was the poor operational reliability of the hugger-belt configuration, which included belt tracking and belt wear. In addition, improved feeding and prevention of foreign material build-up needed to be addressed in future designs.
Modifications to alleviate these problems were developed and incorporated in the prototype and the modified design was field tested to demonstrate the mechanical and functional reliability of the redesigned system.

The difficulties experienced with the performance of the proof-of-concept prototype were successfully addressed and resulted in the development of a commercially viable pre-production prototype.

Davis (2002) demonstrated:

- The development of an alternative design of the harvester elevator bowl, which potentially enhances the performance of the current primary extractor.
- The ability to feed billets into a hugger-belt system at commercially viable rates.
- The ability of a hugger-belt system to present billets in a configuration more suitable for effective cleaning than the current chain and slat elevator.
- The enhanced airflow characteristics and cleaning performance offered by the blower type secondary cleaning module.
- The lighter weight and increased stability due to the reduced overturning moment of the elevator assembly.

Further development of the high speed elevator and field trials under commercial conditions were carried out during 2002. The redesigned elevator led to improvements in the ability of the belts to process cane from the full bowl condition. Trials demonstrated its ability to cut at commercial pour rates with excellent cane quality and final EM levels of 3% versus 5% EM from standard machines operating under similar conditions. Some choke ups still occurred but most of these gluts were able to be cleared without the operator leaving the cab. Mud build up proved to be an issue following significant rain.

During normal continuous operation, belt wear was minimal, but during choke ups or belt feed stalls, belt damage was very rapid due to the friction between moving belt and stationary glut. With an automatic belt tracking system belt alignment was not an issue.

The high speed elevator concept was demonstrated to have potential to significantly reduce cane loss and improve cleaning in the harvesting process. No further work on this concept has occurred.

### 3.8.2 Elevator Modifications

In adopting the ‘improved farming system’ a number of modifications are required to harvesting equipment. One of the major modifications required on the harvester is an increase in elevator length associated with the change to wider-row spacings to suit controlled traffic.

Currently there are two possible solutions to this problem and include an extension to the elevator length or to fit a device to carry cane horizontally (such as an extension conveyor or...
powered paddle roller). Elevator extensions are available from both manufacturers with up to 600 mm increase in length.

The conveyor extension and ‘flipper’ roller (Photograph 12) were originally designed and tested by harvesting contractors looking for low-cost, versatile solutions.

Elevator extensions and conveyor extensions increase the length of the elevator (Photograph 13), hence the overturning moment and the instability of the machine. The lean of the harvester from the additional weight also acts to incline the basecutters relative to the row resulting in an uneven level of cut.

Cane loss is a primary problem with the ‘flipper’ roller, as it has the potential to propel a percentage of billets into the secondary extractor or ‘recirculate’ them onto the ground. The speed and position of the roller are crucial in relation to the elevator flights and secondary fan position. A SRDC grower group innovation project has developed a solution to this problem by tipping back the secondary extractor using a wedge insert to avoid cane loss.

These developments have facilitated the adoption of ‘improved farming systems’.
3.8.3 Benefits Delivered

- Elevator extension developments have facilitated the adoption of ‘improved farming systems’ and are demonstrated examples of industry-led solutions to this issue. Some of these have involved repositioning of secondary cleaning systems, however this may be a potential avenue for increased loss.

3.8.4 Research Opportunities

- An independent assessment of the performance of alternative component designs for extending the length of elevators when harvesting in new farming systems. This assessment should be in the context of best setup, potential avenues of loss and functionality.

- Increased delivery capacity of elevators with whole-of-crop harvesting and/or wide-swath harvesting should be investigated. A number of potential solutions (covered, slower) are in use. No quantifiable data is available on their effectiveness and functionality.

3.9 Secondary Cleaning

The standard cane harvester has a secondary cleaning system based on an extractor fan mounted at the exit point of the billets from the chain and slat elevator. The purpose of the system is to offer final-stage cleaning of remaining extraneous matter from the cane billets as they exit the elevator and fall into the haulout vehicle. The standard system comprises a three-bladed axial-flow fan housed in a barrel and discharge of the extracted material is achieved via a directional discharge hood. The fan is driven by a centrally mounted hydraulic motor. Significant issues for the industry are the cleaning performance of the current unit, and its weight, location of centre of gravity and impact on machine stability.

The presentation of cane to the secondary extractor by the conventional chain and flight conveyor, whilst somewhat better than the presentation to the primary extractor, is highly inappropriate for effective cleaning to occur. This inappropriate presentation, along with a range of design constraints, leads to relatively low cleaning efficiencies and excessive cane loss when cane with high vegetative EM is harvested. Whiteing et al. (2002) indicated that the secondary extractor typically removes about 20% of the vegetative EM presented to it. Their data also indicates that cane loss can vary from very low (<0.5 t/ha) under conditions requiring little secondary cleaning to very high (in excess of 7 t/ha) under high EM conditions and at high pour rates. The very high loss conditions corresponded with full or three-quarter blade design when compared with standard blades.

3.9.1 Blower Cleaning System

All pneumatic cleaning systems have an inherent relationship between pour rate, EM and cane loss, however optimisation of design can enhance trash removal efficiency while
reducing cane loss. An alternative approach to secondary cleaning was developed by Norris and Davis (2001).

The development of a cleaning system in conjunction with a high-speed hugger-belt system offered the potential to present an even layer of material to the secondary cleaning system at a velocity that could be optimised for the subsequent cleaning operation. After consideration of a range of potential secondary cleaning system designs, this system was judged to have the most effective cleaning.

The system improves the conventional cleaning system, although the main objective of the project was to develop a lightweight cleaning system. Initial investigations indicated the use of blowers for the air supply and had considerable potential including:

- High efficiency
- Low maintenance as clean air passes through the fan minimising wear
- Lower weight.

The conventional extractor-type cleaning system has an inherent aerodynamic efficiency of about 30-40% (MF RandD Design Notes), with additional power being used to process the trash and billets passing through it. The power consumption for this function typically at least equals that required for the pumping of air. Typically, the hydraulic power required for the secondary cleaning system is about 20-33 kW (assuming 1500-2500 psi operating pressure and 30.6 gpm oil flow). In contrast, well-designed blower systems demonstrate aerodynamic efficiencies of about 80% (Bleier 1997). Hence, if cleaning potential is related to total energy in the airflow, significant potential reductions in the energy required for the cleaning process could be achieved by a blower-based system, whilst similar cleaning potential is maintained. Alternatively, more air power is available for cleaning, whilst the same installed power is maintained.

Modelling was undertaken by Norris and Davis (2001) using both dilute phase and computational fluid dynamics to assess the suitability of blower systems. This indicated the desirability of a broad air jet of moderate to high velocity, typical of the output of a centrifugal flow fan, rather than an airstream of the lower velocities usually associated with an axial flow fan. The length-to-width requirement of the air jet, along with the desirability of parallel airflow, ruled against the choice of an axial flow fan in conventional configuration.

The design was based on a combination of axial and centrifugal airflow principles. Twin axial-flow fans on a common shaft supply air to each end of a concentric cylinder with the air exiting this cylinder by a tangential draw-off duct. In this arrangement, the air swirl component generated downstream of the fans can be captured and utilised through the scroll effect of the cylinder and draw-off duct.
The cleaning efficiency of the blower system was related to the pour rate (as expected) and at 60 t/hr was 70% efficient and at 100 t/hr was 52% efficient. Since billets do not pass through an extractor fan, cane loss can be determined accurately and simply by determining the weight of billets rejected with the trash as a proportion of the total weight of billets before the cleaning pass. Cane loss was typically between 1% and 3% for the blower cleaning system.

Results from 2002 field trials with this system indicate that cane loss was between 0.02% and 0.05% with EM removal of 40% of what it receives (C Whiteing 2008 pers comm.). A standard extractor removes approximately 20% of the EM that it receives at a cane loss of 2% (Whiteing et al. 2002).

### 3.9.2 Benefits Delivered

- The concept of two-stage (secondary) cleaning is an appropriate design criteria for harvesters.

- Secondary cleaning efficiency of current extractor type systems is related to pour rate as expected.

- Research data indicates that with current extractor type cleaning systems cane loss can vary from very low (<0.5 t/ha) under conditions requiring little secondary cleaning to very high (in excess of 7 t/ha) under high EM conditions and at high pour rates. This has raised awareness of the performance of the secondary extractor.

- Alternative secondary cleaning systems based on blower type arrangements have demonstrated improved cleaning efficiency and lower losses. However, significant redesign of the elevator is required for inclusion of these concepts.
3.10 Instrumentation and Controls

Early harvesters were fitted with minimum instrumentation and cabs and controls were of very basic designs. Later machines have replaced cable-hydraulic controls with electric controls for improved operator ergonomics.

Basecutter position and pressure, chopper pressure, engine monitoring, hydraulic oil temperature and primary extractor fan speed are displayed as a minimum. Harvesters currently available in Australia do not have ground-speed monitors as standard.

In-cab display instruments developed through research include the cane loss monitor, top roller position (to indicate pour rate), harvest performance and yield-monitoring systems.

Developments in cabin shape and interior architecture has advanced in line with other agricultural equipment technology. This has been more rapid since the acquisition of Cameco and Austoft by John Deere and Case IH respectively where cabin shape components from other product lines such as cotton picker cabins etc have been used.

Cabins now incorporate improved visibility (curved glass), electronic operating controls (joystick technology), adjustable headlights and improved seating. The JD3500 series machines also include a supervisor or trainee seat.

Additional developments include improved accessibility, with a cabin tilt capability on Case IH Austoft machines. The titled cabin provides convenient access to the front of the engine compartment for servicing and maintenance, and allows rapid access to beneath the cabin for cleaning and removal of fire hazards.

However, the controls still lack the basic instrumentation like ground speed and fuel consumption afforded to other agricultural machines such as tractors.

3.10.1 Ergonomic Cabin

Since the advent of mechanical cane harvesters, there has been continuing input by manufacturers and researchers to evaluate and improve these machines (Dick 1995). Limited visibility and cabin layout make it difficult for an operator to concentrate on all key areas and thus minimise cane loss.

Dick (1995) developed a state-of-the-art ergonomic cabin to provide the operator with greater comfort and operating ease. This cabin improved all round visibility, and controls were modified for ease of operation. The move from manual hydraulic control with cable/levers to direct electronic control of hydraulic systems was initiated. Testing was undertaken and, after favourable review, Austoft Industries adopted this technology on production machines. Since this initial research, manufacturers have continually upgraded cabin ergonomics and now are equivalent in quality to cabins of other agricultural machines.
3.10.2 Benefits Delivered

• The development of an ergonomic cabin raised awareness with operator comfort and operating ease and provided the impetus for manufacturers to incorporate new technology into cabin designs.

3.11 Benefits Delivered from Component Research

Component research has been the catalyst for novel industry-led approaches to improve the performance of machines and for world-leading technological innovation in mechanical harvesting.

The majority of concepts developed from this component research have manifested as retrofit options for the layout of the standard Australian type machine. The rationale for this approach has been that alternative concepts which require a major re-design of this layout were seen as medium to long-term developments by the manufacturers. As such, the research effort has been expended on the manipulation of concepts within the constraints of the current harvester layout.

Retro-fit developments can require significant capital investment. The economic state of the industry in recent times combined with the additional costs that these developments impose on harvester operators from which in most cases they receive no benefit, have lowered their adoption rate. That is, the improvements in reduced damage and field losses of cane and juice that the majority of these developments offer, the harvester operator receives no direct benefit. Hence, there is no incentive to invest in this capital.

Notwithstanding the above issues, there have been numerous benefits which have flowed directly and indirectly to the Australian sugar industry based on component research. These include:

• A fundamental understanding of the machine-crop interactions in particular the principles and concepts associated with gathering, feeding, basecutting, billeting and cleaning of sugarcane. This has raised awareness of the issues involved during these processes.

• Development of an alternative gathering system for cane harvesters. Developed to a commercial product, 16 units sold in Australia and overseas, impetus for manufacturers to adopt alternative gathering systems on later model machines.

• Alternative forward-feeding geometries. Quantified improved feeding in large green crops. Design concepts embodied in designs of machines modified for new farming systems.

• Demonstrated the concept of zero knockdown whilst still providing effective butt-first feeding of cane

• Fundamental investigation on the cutting of sugarcane – led to enhanced knowledge and quantified losses and damage in these processes (e.g. knockdown, basecutting).
These have underpinned HBP guidelines in particular farming for harvesting (row profile, optimum forward speeds etc).

- Quantified the performance of rotary-pinch chopping systems. Benefits to industry have been through understanding the feed train/chopper drum relationships to minimise cane and juice losses. This work underpinned the HBP guidelines for chopper setup and operation.

- Demonstrated that in rotary-pinch chopper systems (available at that time) that high pour rates lead to high losses even at optimum setup.

- Field losses from the rotary-pinch chopper system are expected to be higher than those measured under test rig conditions.

- Highlighted that the billeting system is an area of high loss. Hence initiated a program of research investigating alternative chopper designs to minimise sucrose losses and overcome limitations re billet length distribution for improved bulk density.

- Improved billet quality and length distribution from synchronised feed train/chopper system. Direct benefit through improved seed quality and performance of billet planters.

- Research on cleaning system design has shown that a major harvester redesign is required for major advances. Current designs have been optimised with an understanding of the impacts of fan speed on cane loss. Commercial products such as the Anti-vortex fan design have been commercially adopted by manufacturers. Alternative concepts (e.g. blowers) have demonstrated the potential for minimising cane loss.

- Industry funded research on the development of an ergonomic cabin provided the impetus for manufacturers to incorporate new technology into cabin designs.

A number of developments have been adopted by harvester manufacturers. Most notably are gathering systems with large diameter, 45degree spirals, feed train rollers operating at similar speeds and matched to chopper drum speeds and the Anti-vortex fan. Whilst the industry may consider that these constitute leakage of Australian research for the benefit of international competitors, these developments have significantly improved the performance of harvesters from which the Australian industry benefits. In addition, these developments such as alternative gathering systems would not have even occurred without the assistance of industry research.

3.12 Machine Component Research Opportunities

John Deere perceives the worldwide market for cane harvesters to be small, relative to the market for 'mainstream products'. Hence, the company is reluctant to invest large sums in developing new technology (N Toft 2008 pers comm.). Therefore this statement provides the Australian industry with a key research challenge.
The research opportunities for machine components will be based on the demand for machine purpose and design considerations. For example green versus whole-of-crop harvesting versus wide-swath harvesting.

- In harvesting systems where the differentiation and removal of tops and green leaf is required an improved topping system will become paramount (dry leaf with cane, green leaf rejected). The development of a topping system should be a priority which includes:
  - Improved gathering ability, shredding and directional control of chopped material
  - Greater reach height and angle of approach to erect stalks.

- The current crop divider linkage system tends to be dynamically unstable. An industry-led, simple, cost-effective solution (dynamically stable) for controlling the height of the crop dividers should be encouraged.

- The impact of alternative component designs (e.g. modified side trim knives) on harvesting losses should be quantified.

- There are fundamental knowledge gaps in machine forward-feeding performance with respect to whole-of-crop harvesting and green cane harvesting at current industry pour rate levels. These include:
  - The impact of volumetric capacity and feeding efficiency when harvesting for high biomass systems (whole-of-crop, high pour rate).
  - The concept of zero knockdown and the impact of knockdown on stool damage and sugar losses should be further explored.
  - There is a fundamental knowledge gap with respect to the forward attitude of the basecutters to the ground. That is, what is the optimum blade angle and the effect of changing blade angle on quality of cut, losses and dirt in the cane supply.
  - Alternative concepts for cutting of sugarcane should be considered by industry.
  - An education process for farming for harvesting with respect to row profile and ‘fill-in’ should be an industry priority, as crop presentation has been demonstrated to be just as critical as machine setup and design.
  - The impact of current industry pour rates on feed train/chopper system configurations with a particular emphasis on resulting damage and sucrose losses is a priority.
  - An independent assessment of the performance of alternative component designs for extending the length of elevators when harvesting in new farming systems. This assessment should be in the context of best setup, potential avenues of loss and functionality.
  - Increased delivery capacity of elevators with whole-of-crop harvesting and/or wide-swath harvesting should be considered a priority by industry.
4 HARVESTER PERFORMANCE – THE YIELD V QUALITY IMPERATIVE

The process of harvesting sugarcane to produce a product free of extraneous matter (EM) has always been accompanied by the loss of millable cane. This loss increased considerably with the change from whole-stalk to ‘chopped cane’ harvesting and has been exacerbated with the move into green-cane harvesting with the increased demand for removal of EM (Brotherton 2002).

There has always been an industry awareness of the cane loss problem, but the magnitude of losses has been hidden to a large extent by the invisible nature of the loss. That is, desiccated billets are difficult to identify and cane and sugar loss is difficult to measure. Industry has demanded increased machine throughput, and this has, to some extent, overridden the effectiveness of measures to minimise cane loss in harvesting.

4.1 Loss Processes

Harvesting losses occur throughout the harvesting process, from feeding and gathering through to chopping, cleaning, transferring to in-field haulouts and transfer to rail or road transport.

The gathering process may not pickup all the cane stalks and/or damage the stalk, particularly in lodged heavy crops. When stalks are damaged, particles of juice-bearing material and juice itself are expelled from the stalk. In basecutting and in the feed train, where the cane is shaken to remove dirt, and subjected to pressure, more damage occurs. Some of the particles, including parts of stalks in the gathering process, are not captured and become ‘ground’ loss. Juice may fall to the ground and become loss, or be transferred onto the billets and trash. In the chopper, not only are juice and particles expelled, but offcuts at the end of stalks are formed.

In the primary extractor, any material under billet size has a high probability of being expelled with extraneous matter. Thus, loss from the primary extractor is not only from entrained billets and tops where mutilation occurs, but also includes contributions from the damage that occurred earlier in the process. This, of course, also applies to the secondary extractor. Juice transferred onto ejected material is also lost. Loss and damage levels in all of these processes are generally proportional to pour rate.

Cane loss occurs at many places through the harvesting operation. Gathering, basecutting, feeding, chopping and cleaning all contribute to loss and damage levels and are all affected by pour rate.

Whilst losses have generally been presented as cane loss, the loss of Pol (a sucrose approximation) and loss of CCS (recoverable commercial sugar) have become more relevant indicators in recent years as these are the intended products of the current industry. These parameters also respond to stalk degradation and deterioration that are omitted in cane loss.

In practice, the material left in the field includes that dropped from all harvesting processes (e.g. gathering, basecutting, feed train, chopping, cleaning). It is difficult, with the exception
of whole stalks, damaged billets and material passed through the extractors to identify the material lost in a specific process from the total material gathered. In much of the literature this distinction is blurred.

### 4.1.1 Quantifying Loss

Brotherton (2002) considered that an accurate, absolute magnitude of loss is necessary for economic evaluation of harvesting losses. An accurate magnitude, while not absolute, is necessary for economic comparison of treatments (modifications of equipment or procedures). Technical comparisons may not need this accuracy, provided statistical significance is achieved.

A number of methods have been used to quantify cane and sugar loss, including direct collection (the ‘blue tarp’), indirect measurement (mass balance techniques) and inferential measurement (cane loss monitor). The following is an outline of the absolute magnitude of loss from the various harvester processes and the total loss.

The **direct collection method** involves collecting the material lost per unit area through the ‘blue-tarp’ method or the pickup or scrap recovery method. It is theoretically preferable because only the one error, that of the weight measurement, is involved (Brotherton 2002).

The ‘blue tarp’ method was developed to reduce the labour resources required by concentrating on the primary cleaning fan discharge. It involves placing tarpaulins beside the cane row to be harvested, so that material thrown from the harvester extractor/s is directed onto the tarpaulin as the machine passes. The sugarcane fragments are then sorted from this mass and weighed to give an estimate of the minimum loss. The actual cane loss is often much higher than indicated by the tarp method due to the complete destruction of cane passing through the extractor fan. The pickup or scrap recovery method employs the same techniques as the tarp method except material from a measured quadrat on the ground is sorted rather than using a tarp.

However, in practice, the sorting of material from EM and collection is labour intensive and the shattering of cane into juice and minute particles can lead to sever underestimation loss (de Beer et al. 1992). Thus, the mass of cane fragments represents only a portion of the sucrose loss, as much of the sucrose is lost as juice, which is not collected by this method. Consequently the mass of cane fragments is multiplied by a factor to account for the juice component.

Linedale et al. (1993), Linedale and Ridge (1996), Linedale (1997) developed and refined the ‘blue tarp’ method of quantifying extractor loss. They used a constant multiplying factor of two applied to the ‘blue tarp’ loss to approximate material balance loss. Norris and James (2001) demonstrated that the multiplying factor was a non-linear function of fan speed.

The ‘blue tarp’ method indicates a minimum value for each measurement, since the highly disintegrated material and juice dispersed and evaporated are unlikely to have been collected. The “blue tarp” method (no factor) shows extractor losses approximately 0-8 t/ha. Total cane loss recorded (excluding adjusted ‘tarp’ losses) from replicated trials varied from 0.9-5.6% in Australia and 2.8-15.2% overseas (Brotherton 2002).

**Indirect measurement** involves determining the yield per unit area before and after harvest. The loss is the difference between these calculated through the material balance method.
(on cane) or the Pol and CCS balance method. This method has the disadvantage that the loss measurement is a difference that has contributions from at least two error sources and, in practice from several (Brotherton 2002).

Whiteing et al. (2001) and Davis and Norris (2001) showed that total losses ranged from 4.1-21.1% using mass balance techniques. Added to this is an ’invisible’ loss of 2.17-3.17%, measured in well-replicated trials in Brazil. This invisible loss comprises 0.79% from basecutter and 2.38%, from the feed train, chopper and cleaning systems at a fan speed 1350 rpm (1.38% from a fan speed of 1000 rpm) (Brotherton 2002).

The above summary illustrates the variability of cane loss depending on the circumstances, and the potential for extremely significant losses.

The extent and complexity of this problem is demonstrated in trials by Berding (2002). In a series of trials over two seasons in green cane, the CCS of the green cane supplied to the mill was virtually unchanged from that of the gross available material in the field. This was in spite of the obvious removal of extraneous matter during harvest. In effect, as much sound cane was discarded as was extraneous matter. Harvesting produced only a small increase in the CCS of the whole crop, and redistributed sugar back into the paddock through the extractor. The data gathered caused researchers to “strongly question the efficiency and rationale of current harvesting technology…an expensive process does little to enrich CCS …and only marginally reduces the EM content” Berding (2002).

**Inferential measurement** uses a parameter (e.g. acoustic), which requires a calibration reference against a known loss. This reference must be as precise and accurate as possible.

Dick et al. (1991) and Dick and Grevis-James (1992) reported on the development of an electronic cane loss monitor for harvesters. Dick et al. (1991) conducted a number of static trials, where a known mass of cane and EM were fed into a harvester. These trials showed a good correlation between cane loss monitor reading and mass balance derived extractor losses. Dick and Grevis-James (1992) showed that the cane loss monitor gave a good indication of relative cane loss. However, the need for calibration of the sensor was shown to be critical. Whiteing et al. (2004) in a review of fan blade and hood mounted sensors found that neither sensor was able to distinguish actual billets hits, and no relationship was found linking voltage output to number of billet hits and mass of cane loss.

### 4.1.2 Methods to Measure In-Field Sugar Loss

At present there are two methods to measure the sucrose lost through the primary cleaning fan – blue tarp and mass balance methods. The mass balance method provides the most accurate measurement of sucrose loss, however it requires a large investment of time and money due to the setup of dedicated test facilities and the associated labour intensive nature of the trial work. Extension to field based trials is also made more difficult, as the variability of the crop within the field necessitates significant replication, thus further adding to the cost of the method.

Sichter et al. (2005) investigated the nature of the sugar deposited on field residue to assess whether it is of any millable value. Sichter et al. (2005) also investigated methods for quick and accurate measurement of the sugar concentration from trash and field residue samples.
Sugar transferred onto trash is readily extracted by a washing process, however some preparation or particle reduction may be necessary. Sugar in field residue includes trash and cane pulp fragments from the extractors. Sugar in field residue is a little more difficult to extract, requiring either fine preparation (e.g. Jeffco cutter grinder) to open 100% of juice cells prior to simple water wash extraction or a coarser preparation and a hydraulic press to achieve extraction (Sichter et al. 2005).

Sichter et al. (2005) assessed the validity of a simple rapid method involving preparation of trash with a garden mulcher, tumbling a known amount of trash and water and extracting the liquid from the trash using a hydraulic press. The sugar solution was analysed for Brix and Pol by polarimetry and high performance liquid chromatography (HPLC). In initial laboratory trials a sugar recovery of between 82% to 98% (average 90%) was obtained.

The suitability of this technique to measure the sugar content in samples form field trials was also assessed. Sichter et al. (2005) found that this technique was effective in accounting for 55% of sugar loss from the harvester as determined by a replicated mass balance.

The limitation with this technique is that it requires laboratory preparation of samples, is labour intensive and delays involved in transporting and processing samples resulted in deterioration in sucrose content.

Doherty et al. (2007) investigated a number of alternative methods to measure in-field sugar loss during harvesting including enzymatic and Near Infra-Red spectroscopy (NIRS) techniques. Enzymatic methods were found to be cumbersome and impractical to measure sucrose in-field.

NIRS can be used to assess sugar content of sugarcane and a number of NIR systems are currently used within sugar mills for assessment of incoming cane quality. However, units are not portable, and are expensive (ca. $150,000).

Doherty et al. (2007) evaluated a lower cost, portable unit operating over a shorter wavelength range (SWNIR) in comparison using three populations of cane samples. SWNIR was demonstrated to be capable of predicting sugar content of the trash samples used. The standard error of prediction was less than the standard deviation (SD) of the samples for the total set of samples, which included sucrose and billet amended samples. However, it was not less than the SD of the ‘pure trash’ samples only. This implies that neither SWNIR nor NIR devices can be used to assess sugar loss during harvesting.

A ‘reference method’ for assessment of sugar in harvester trash was established, involving grinding of trash material in an equal weight of water and assessment of the Brix of the resulting solution (Doherty et al. 2007). Doherty et al. (2007) suggests that this method, in an automated form, could form the basis for an in-field measure of harvester sugar-loss efficiency. The development of a mobile, rapid in-field sucrose loss measurement tool is ongoing with funding provided by SRDC through project BSS0318.
4.2 Topper Loss

Topper cane loss is a result of the variability in height of growing points of cane stalks. There is always a compromise between top material taken into the harvester and cane lost.

Fuelling (1981) reported that erect Q90 showed a standard deviation of the preferred topping point of approximately 300 mm. When topping ‘low’ in pre-harvest tests of cane topping, the collection of tops showed a cane loss averaging 4.2% of cane. In the more ‘normal’ trials, the mean cane loss was 0.5 t/ha, possibly not significantly different from zero.

Hurney et al. (1984) in comparative trials with MF305, MF205 and VT6000 harvesters found mean cane loss in burnt cane of 0.28 t/ha and 1.49 t/ha for MF and VT machines respectively.

Fernandez (1992) comments on the use of a simulation of the topping operation and found, that in typical Cuban crops, topping 10-20% above the mean height of the stalk produced a loss of cane of less than 1.0%.

Whiteing et al. (2002) indicated that although topping reduced yield by 6 t/ha, an increase in CCS of 0.6 units increased grower’s income by $110/ha. In this trial, trash reduced by 1% and tops reduced by 5%. This indicates that topping is certainly a beneficial process to significantly reduce extraneous matter and thereby increase industry returns and improve cane quality.

The operation of the topper is very much dependent on the evenness of the crop and operator setting. If operated at the correct height then cane losses are minimised. Whiteing et al (2002) reported that in erect cane, toppers generally do not exceed 80% tops capture efficiency.

4.3 Gathering and Pick-up loss

This loss is due to failure to pick up lodged stalks, stalks knocked down from the previous harvest row, parts of stalks cut by side trim knives, stalks broken off during the gathering process and dropped.

Gathering and pick-up losses are affected to a large extent on the presentation of the crop to the harvester. These losses are minimised with properly filled in rows, consistent row spacing and with a row profile that matches the harvester basecutter setup.

Improved communication between grower and operator helps identify the best crop presentation to suit individual harvester setups.

Mason et al. (1978) reported that in replicated trials, total cane picked up after harvest weighed 2-10 t/ha. This included extractor material.

Fuelling et al. (1979) collected wholestalk cane (>250mm) not picked up by the harvester and found that loss increased as basecutter setting was lowered. Cane loss ranged from
zero to 4.5 t/ha in erect cane, with an average of 0.6 t/ha with the basecutter operating at ground level. A loss of 8.3 t/ha was measured in lodged conditions.

Bundaberg Sugar (2001) reported an average harvester loss excluding extractor loss of 1 t/ha from the average yield of 89 t/ha across a survey of harvests in the Bundaberg region.

Davis and Norris (2001) reported ground losses of 3.0 and 4.1 t/ha for erect and lodged crop conditions respectively. These measurements were taken by physical collection of material from the field and it is stated that these averaged results were from extremely variable data.

Whiteing and Kingston (2008) measured ‘pick-up’ losses by finding and weighing all cane stalks after harvest in trials at Bundaberg and Mackay. At Bundaberg, over a three year period, they found pick-up losses for a standard harvester setup to range from 0.4 t/ha in a low yielding crop (68.4 t/ha) to 1.4 t/ha in a large erect crop (99.2 t/ha). Similarly, at Mackay, they found pick-up losses for the same harvester setup to range from 0.6 t/ha in a low yielding crop (68.9 t/ha) to 2.2 t/ha in a very large erect crop (123.7 t/ha).

Whiteing and Kingston (2008) also highlighted there is a real opportunity to reduce levels of pick-up loss through improved crop presentation such as row profile, filled in rows and row spacing.

4.4 Basecutter and Feed Train Losses

The severing of whole stalks and the transfer of cane to the chopper are sources of cane damage with juice and other fibrous material being expelled. This is a source of cane and sugar loss that was disregarded for some years. In early studies, the extent of cane damage itself was a source of concern from the deterioration aspect rather than for the loss aspect (Brotherton 2002).

The action of knocking down the cane stalks for butt-first feeding and the impact nature of the basecutting action produces juice, fine particles and cane fragments, only some of which may be transferred or incorporated into the material stream heading up the feed train.

The feed train components can also create damage to material if pour rates exceed the volumetric capacity of the system and also in the process of agitation in an attempt to dislodge dirt. Thus, not only is solid material lost, but also the damaged material remaining will have lost juice with a potential loss of sucrose.

The industry continues to argue that transferred juice is recoverable at the mill, however this is manifested as reduced recovery rates (N Sichter 2008 pers comm.). It is the opinion of the authors that this issue must be addressed at its source, that is, by minimising the sugar and cane loss during the harvesting process.

Kroes and Harris (1994) investigated basecutter parameters on the quality of cut. They concluded that post-cut impacts are the major cause of shattering of stools. That is on completion of the cut, the stool returns to an upright position and the following blade impacts resulting in either the removal of the small top piece or complete shattering of the stool. Increased feed rate also increased damage to the cane.

Kroes (1997) in laboratory trials simulated knockdown and basecutter damage on billets and determined the likelihood of these fragments being removed by the primary extractor. Field
trials were undertaken in green cane with the harvested cane collected and sorted to allow mass comparisons between extracted and non-extracted treatments. He found splitting and separating of billets into smaller fragments was responsible for 4.2% of the cane loss.

Davis and Norris (2001) reported basecutter losses of 9.7 t/ha (lodged cane) and 3.0 t/ha (erect cane), feed train losses of 7.0 and 5.3 t/ha, respectively, and ground losses of 3.0 and 4.1 t/ha, respectively. These measurements were taken by physical collection of material from the field and it is stated that these averaged results were from extremely variable data. A significant decrease in CCS of stalk material was reported. Davis and Norris (2001) reported that crop presentation has significant impact on basecutter and feed train losses.

Whiteing and Kingston (2008) measured ‘ground’ losses in harvester trials at Bundaberg and Mackay. They defined ‘ground’ losses as all small cane fragments and short butts associated with basecutter shattering and underground snaps that leave a small section of cane stalk butt after harvest. These ‘ground’ losses are essentially knockdown and basecutter losses.

At Bundaberg, over a three year period, they found ‘ground’ losses for a standard harvester setup to range from 0.1 t/ha (measured crop yield of 68.4 t/ha) to 0.38 t/ha (crop yield 99.2 t/ha). Similarly, at Mackay, they found pick-up losses for the same harvester setup to range from 0.5 t/ha (crop yield 68.9 t/ha) to 0.78 t/ha in the plant crop yield of 65.8 t/ha.

These results compare with a zero knockdown harvester forward-feeding configuration in the same trials of 0.02 t/ha (56.8 t/ha crop yield) to 0.28 t/ha (74.5 t/ha crop yield) at Bundaberg.

Similarly, with a zero knockdown harvester forward-feeding configuration in Mackay trials, Whiteing and Kingston (2008) found ‘ground’ losses to range from 0.29 t/ha (crop yield 65.1 t/ha) to 0.19 t/ha in the plant crop (crop yield 65.9 t/ha).

Whiteing and Kingston (2008) found that ground losses can be reduced by improved harvester forward-feeding configuration. However, they found major inconsistencies in the damage levels recorded due to external non-harvester related variability.

For example filling-in and hilling-up was found to be the most significant crop presentation variable. Incomplete hill-up, that leaves a hollow in the centre of the row results in stalks being cut above ground level and correspondingly increased damage and ground loss.

Whiteing and Kingston (2008) hypothesis is that if crop presentation issues have been able to override the expected effects of harvester design improvements, then attention to detail in preparing cane crops for harvest is even more vital than previously suggested.

4.5 Chopper Losses and Billet length

A number of studies have assessed the losses associated with the billeting process, with the main focus being on the rotary-pinch chopping system.

Moller (1975) was the first to evaluate the loss in mass between wholestalk cane entering a ‘chopped cane’ harvester and the mass of millable billets. He fed stripped and topped cane in a stationary MF102 harvester and reported an estimated chopper loss (nominally juice and fine material) of around 4%. No pour rate was reported.
Moller (1975) also reported on Massey Ferguson’s laboratory scale testing of a rotary-pinch chopper system producing 300 mm nominal billets. The chopper system produced small billets and fragments of cane amounting to 3.4% of the feed and there was an unexplained loss of 0.5% of the original weight.

Fuelling and Henkel (1979) examined the relationship in the field between tonnage cut, chopper knife condition and billet quality on Toft 6000 (swinging knife), MF205 (MF rotary pinch chop) and Class 1400 (Class rotary-pinch chop). They found chopper system design significantly impacted on billet quality and that billet quality was typically 10% lower in lodged cane than in erect cane.

Fuelling (1980) attempted to quantify chopper losses with limited facilities. He weighed and placed bundles of 100 stalks on the ground and driven over by the harvester. This method was able to achieve controlled feed into the harvester at ‘commercial’ pour rates. The magnitude of chopper losses was determined by mass balance. Whilst the results were inconsistent, losses of about 2.5% were found.

Dick and Grevis-James (1992) in calibrating their cane loss monitor, reported a chopper loss of 1.9% in test-facility trials using material balance.

In the early 1980’s, BSES undertook a series of trials in conjunction with Versatile-Toft, during the development of the rotary-pinch chopper system to be used in the 7000 production model (Norris et al. 2000). The trials were undertaken by feeding a stationary harvester with pre-weighed, stripped and topped cane on a 12 m long conveyor at a pour rate of 60 t/hr. Results indicated losses in the order of 3% with a nominal billet length of 250 mm.

Norris et al. (2000) developed a functional full scale chopper test rig facility (Photograph 7). The facility was designed to allow rotary-pinch chopper systems to be mounted as interchangeable modules, isolation of the various hydraulic circuits to control component speeds and a wholestalk cane feed system for controlled cane feed. The test rig was also instrumented to measure axial and traverse forces, component speeds and operating pressures.

Hockings et al. (2000) reported on rotary-pinch chopper system tests in the test rig facility. Cane loss was assessed by the mass balance between feed cane weight and that of billets, plus large billet pieces. The statistical significance of the mean results is not given, but chopper losses were 1.0-3.0% (derived from charts). Norris et al. (2000) provided plots indicating the dependence of damage and loss on operational parameters. The mean loss was 3.4% across all chopper systems tested in optimal set-up.

Lamb et al. (2008) measured the mass loss per cut per metre in trials of a proof-of-concept single-drum chopper system. They found a 0.8% mass loss per cut per metre with a 200 mm billet length at pour rates of 150 t/hr and 300 t/hr. This compares with Davis and Norris (2002) who measured an average ‘0.6 to 0.7% mass loss per cut per metre’ from the best rotary-pinch chopper system (12-inch, 2 blade) under full scale test rig trials at billet lengths of 250 mm and pour rates of 120 t/hr and 240 t/hr.

However, they note that perfectly sharp blades were used in Davis and Norris (2002) trials and this is not the situation for rotary pinch choppers in the field. Similarly, Davis and Norris (2002) used choppers with 2 and 3 blades per drum (for 12-inch diameter drums) and 3 and 4 blades per drum (for 15-inch diameter drums) whereas 5 and 6 blade per drum rotary-
pinch chopper systems are now being supplied, with the push towards higher pour rates and shorter billets. Consequently, the actual mass loss in the field is estimated to be well over 1% per cut per metre (Lamb et al. 2008).

Lamb et al. (2008) claim that with knowledge gained from high speed video analysis of the proof-of-concept trials, and the engineering changes that can be made to improve performance, results of better than 0.6% mass loss per cut per metre are expected when set-up of the single drum chopper system is optimised.

If this loss per cut per metre is realised along with the advantage of varying billet length independently of the feed train then there is significant benefits to be gained for the industry from this type of chopper system.

Gomez et al. (2006) used mass balance measurements to determine sugar losses from billeting. They defined billeting losses as wholestalk CCS minus the CCS of clean billets. Comparative studies of a John Deere 3510 harvester harvesting in green and burnt cane have shown that billeting loss ranged between 0.6 % (2002) to 5.5 % (2005) in green cane and 1.8 % (2002) to 5.5 % (2005) in burnt cane of the total available sugar per hectare. The higher sugar loss in 2005 was attributed to higher temperatures at the time of harvest.

Vitale and Domanti (1997) examined the effect of billet length on bin weight, cane deterioration, EM and cane loss. Most historical data supports the argument that reducing billet length increased bin weights and decreases EM levels. The main costs influenced by billet length are cane transport, cane deterioration, EM and cane loss. The relationship between billet length and bin weight developed in the model suggests that a 1% change in billet length produces a 0.5% change in bin weight. Obviously this is an important economic factor when analysing the impact of feed train optimisation, which usually results in a billet length increase. The model made some attempt to calculate the cost of additional EM and cane loss but used limited data. A sensitivity analysis indicated that cane deterioration cost, harvest-transport cost, bin maintenance cost and bin weight relationships had only minor impacts on optimum billet length, while EM and cane loss relationships had far greater effects. Until the links between billet length, cleaning efficiency and cane loss are more thoroughly understood, it is difficult to define an 'optimum' billet length for any given situation.

James (2003) showed that, over replicated harvests, the CCS obtained cutting short billets averaged up to 1.36 units lower than that obtained cutting long billets. The short billets had a lower juice Brix and lower juice purity than the long billets. The differences were statistically highly significant. This is an interesting result and the cause deserves further investigation. This loss compounds with the weight loss determined by direct measurement. Data from the chopper test rig and field trials suggest chopper losses in the order of 7% in a sub-optimal set up. An optimised feed train cutting a longer billet can potentially reduce these losses by 5%.

Billet length/fanspeed interaction trials in north Queensland demonstrated that increasing billet length increased the biomass per hectare yield (James 2003). These increases ranged in estimated magnitude (as percent of trial mean) from 2.25 to 5.5% additional tonnes biomass per hectare. As these increases were not met by corresponding increases in measured percentage trash or fibre levels, it could be hypothesised that these yield increases were due to a net decrease in the magnitude of associated cane and juice loss with the long billet treatments.
Highly significant decreases in biomass yield per hectare were observed as primary extractor fan speed increased. The estimated magnitude of this decrease in biomass yield was 2.7%-10.9% and could not be explained by decreases in trash or fibre levels. It is therefore likely that these results represent increased loss of millable cane through the primary extractor fan. This supports the results of Whiteing et al. (2002).

There was a significant interaction (<5%) between billet length and fan speed. This interaction was interpreted as an indication that shorter billet lengths were more prone to loss through the primary extractor. Figure 6 shows the impact of fanspeed and billet length on recoverable sugar in one of three trials.

![Figure 14: The Interacting Effects of Fan Speed and Billet Length upon Sugar Yield (James 2003)](image)

Results from these field trials showed that the combination of increased CCS and increased biomass per hectare led to an overall detectable increase of between 0.48 and 0.53 t/ha of CCS as billet length increased. As a percentage of trial means, this equates to a recoverable per hectare sugar yield increase of 4.3-5.9%, with this result being highly statistically significant (<0.01%) in two of the three trials. This result is considered to be of substantial importance, and demands further research.

The trials demonstrated that overall recoverable per hectare sugar yields decreased significantly as fan speed increased from 1050 to 1250 rpm. As a percentage of trial means this equates to a drop in recoverable sugar yield of between 0.9 and 11.9%. It is interesting to note here that the lower drop occurred in standing irrigated cane, whereas the larger drop occurred in a slightly lodged sprawled crop of cane. This could be interpreted as a loose indication that the evenness of feed and crop conditions can have a significant effect upon cane loss.

Bin weight was inversely proportional to observed billet length, and this effect was significant with all trials (Table 3). This decrease was estimated at between 0.52 (Singh) and 1.52
tonnes per bin (Tully). These figures, when converted to a percentage of the trial mean were 4.4% to 15.5% additional weight per bin with shorter billets. Actual billet lengths for each trial are given below.

**TABLE 2: EFFECT OF BILLET LENGTH UPON BIN WEIGHT (JAMES 2003)**

<table>
<thead>
<tr>
<th>Trial</th>
<th>Variety</th>
<th>Billet length (mm)</th>
<th>% Weight increase</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>short</td>
<td>long</td>
</tr>
<tr>
<td>Singh</td>
<td>Q120, 1R</td>
<td>130</td>
<td>170</td>
</tr>
<tr>
<td>Sciacca</td>
<td>Q120, 2R</td>
<td>175</td>
<td>204</td>
</tr>
<tr>
<td>Tully</td>
<td>Q174A, 2R</td>
<td>162</td>
<td>202</td>
</tr>
</tbody>
</table>

The impact of billet length on bin weight has been modelled using an adaptation of Parkhouse and Kelly’s material packing model. The graph below gives an indication of the billet length/bin weight interaction for the Mossman district.

![The Estimated Effect of Billet Length and Diameter upon Bin Weights (Adapted from Parkhouse and Kelly, 1995)](image)

**FIGURE 15: THE ESTIMATED EFFECTS OF BILLET LENGTH AND DIAMETER UPON AVERAGE BIN WEIGHTS FOR MOSSMAN HIGH SIDED BINS (JAMES 2003)**

Davis (2006) compared billet length distribution, packing density and bin weight in trials between a standard and modified three-blades per drum rotary-pinch chopper system. He found that standard unsynchronised (‘short’) billet setting resulted in 37% by weight of billets falling within the range of 225 to 237 mm with 75% of billets within 25 mm of the mean target length. This translated into a packing density of 380 kg/m³ at a 2.9% EM level.

For a synchronised (‘long’) billet length setting, 39% by weight of billets fell within the range of 262 to 275 mm and represented a left skewed distribution around this mean target length, with approximately 75% of billets within 25 mm of this length. This translated into a packing density of 365 kg/m³ (2.2% EM) a decrease of 4% from the unsynchronised (‘short’) billet setting and is less than the average % increase found by James (2003). However it is noted that four-blades per drum chopper systems were used in James (2003) trials.
The recorded billet length distribution from samples taken from the synchronised ('long') billet length setting treatment of the modified chopper was approximately 24% by weight of billets falling within the range of 200 to 225 mm and 48% falling within the range of 275-300 mm. These were the target billet lengths. The packing density of the modified chopper uniform length billet treatment was found to be 375 kg/m³ with a corresponding average reduction in bin weight from the standard chopper variable length billets of 1% (1.3% EM). Alternatively, an increase in bin weight of 2.7% was found when compared with the standard chopper uniform length billets.

Whilst, the trash level decreased with uniform billet lengths, this did not translate to an increase in packing density. This result supports the theory hypothesised by Davis and Norris (2002) that a more even flow of material from the synchronised feed train/chopper system to the cleaning chamber would result in improved cleaning performance. This contradicts the work by Vitale and Domanti (1997) who found that reducing billet length decreased EM levels.

### 4.6 Cleaning Chamber Losses

With a strong focus on minimising EM in the cane supply, the harvesting process has always been accompanied by the loss of millable cane. Green cane harvesting has put increased pressure on harvester operators to remove EM and has increased extractor losses considerably. Industry awareness campaigns have sought to reduce these losses, but cleaning chamber losses continue to be a major cost to the Australian sugar industry.

In the removal of extraneous matter, billets and cane particles can be entrained in the air stream (Clayton and Churchill 1972; Clayton et al. 1985). Much of the particle mass formed previously in the gathering, basecutting, feeding and chopping, but held in the cane stream, may be lost. The transfer of juice onto the extraneous matter during these processes may also be lost during cleaning. In extractor (suction) fans, the material extracted passes through the fan and may be shredded, so that later identification is impossible. Blower fans allow a measure of identification of particles, since these do not pass through the rotating blades.

Because of the variability encountered in cane loss measurement, it is desirable that important parameters eg, field conditions, machine design and special alterations, be reported to aid comprehension of the results.

The many aspects in measurement of cane loss are commented on by Mason et al. (1980). Some method variations have since occurred, but the various classes of methods that have been used to measure cane (and components) loss can be reduced to direct measurement (e.g. 'blue trap'), indirect measurement (mass balance) and inferential measurement (e.g. cane loss monitor). Explanation of these techniques is provided in section 4.1.2.

Mass balance trials were used in early loss performance studies by Moller (1975), Fuelling (1981) and Humney and Ridge (1984). Moller (1975) reported extractor loss of 5.9% whilst Humney and Ridge (1984) showed mean losses of 4.0-4.9% in burnt cane trials.

Ridge et al. (1984) emphasised the importance of replication of in-field measurements and concluded that the use of a test facility in a controlled environment would allow more accurate determinations to be made. To increase the accuracy of results to enable fine-tuning of equipment and techniques they developed a test facility. Ridge and Dick (1987)
reported early results from this development. The system had no normal basecutter operation, so that losses were derived from the feed train, chopper and extractor operations only. In the first series of tests, extractor cane loss was between 4.2-18%.

Dick and Grevis-James (1992) in calibrating their cane loss monitor, reported up to 13% cane loss in test-facility trials using material balance. In later replicated field trials, clean cane material balance was used to standardise the monitor readings. Yield losses of up to 21.1% in untopped green cane were reported.

Shaw and Brotherton (1992) assessed cane loss in green cane harvesting in the Mulgrave area using the ‘blue tarp’ method and a multiplication factor of 2.5. They measured an average cane loss of 8.2 t/ha. They also noted that the purity of juice in the expelled fragmented material was typical of cane stalk, rather than of tops, indicating that the material lost was valuable millable cane.

Linedale et al. (1993) measured extractor losses in both green and burnt cane trials. They found losses as high as 15 t/ha in green cane using the tarp method of estimating cane loss. Based on current knowledge, this was indicative of potentially much higher losses. These trials also demonstrated that extractor losses in green cane were consistently higher than in burnt cane at the same fanspeeds. In field trials, losses averaged 0.6-2 t/ha in burnt cane and 4.3-8.1 t/ha in green cane. They also undertook trials in which the extractor was varied and found that the cane loss increased progressively from 1 t/ha at low speeds to 3-12.3 t/ha at high speeds. The underestimation of cane loss using the tarp in these trials led to the conclusion that ‘optimum’ fanspeeds were quite high (1250+ rpm).

Linedale and Ridge (1996) report a reduction in extractor cane loss in green cane from 10.5 to 3.8 t/ha with a reduction in fan speed. However, the corresponding fan speeds were not reported.

Ridge and Pearce (1996) measured cane losses in their work on extractor system development, both in a test facility and field trials. They reported cane losses up to 22.3%.

Linedale (1997) reported a range of cane loss between 0.9 and 5.6% from all trials in the development of the ‘blue tarp’ system.

Trials by Lindale and Ridge (1996) in Tully and Cairns showed losses of 4.6-18.1%. They saw that ‘while there was a clear advantage in reducing cane loss, the trend to increased EM was also demonstrated, reinforcing the need to continually assess this relationship’.

Bundaberg Sugar (2001) using an unreplicated pick-up method measured extractor losses between 0.45 and 13.1 t/ha (mean 2.45 t/ha).

The underestimation of cane loss from the ‘blue tarp’ method led to a program of replicated field trials comparing total biomass from typical and ‘extractor fans off’ treatments. This mass balance approach has enabled more accurate measurement of extractor losses.

Whiting et al. (2002) assessed the performance of later model machines between 1997 and 2001 with the aim of establishing optimum modes of performance. Material balance was used to measure total loss and they compared ‘blue tarp’ extractor loss with the mass balance loss. Three and four replicates per fanspeed treatment were used. They measured a total cane loss between 0.29-31.66 t/ha (mean 9.57 t/ha) and extractor losses between 0.36 and 8.2 t/ha (mean 2.60 t/ha).
The material balance differences between fanspeed treatment means were significant at the 5% level in only two trials. Extractor loss differences by the ‘blue tarp’ method were significant (5% level) in six cases.

Figure 16 illustrates the results of one of Whiteing et al. (2002) fan speed trials. This shows that ‘blue tarp’ in no way reflects actual cane loss and that a correction factor of up to 15 could be required.

Whiteing et al. (2002) concluded that primary extractor cane loss is primarily determined by fan speed. They developed a relationship between fan speed and probably cane loss as shown in Figure 17.

The lower line on the band of probable loss in Figure 17 represents the minimum loss established using ‘blue tarp’ findings, while the upper line indicates potential high losses seen in difficult conditions found by mass balance methods. Increasing fanspeed beyond 1000 rpm causes a rapid increase in cane loss, but has limited impact on cleaning efficiency with only small reductions in EM. Significantly higher cane loss occurs at high fan speeds, with losses in excess of 20 t/ha being recorded.

Operators need to be aware of the performance characteristics of extractor systems so that they can act to minimise cane loss.
Researchers at Ledesma Mill in Argentina have a long history of harvester research. Their current focus is on green compared to burnt cane harvesting. Gomez et al. (2003) suggest that there would be significant benefit in harvesting green cane, compared to burnt, if extractor losses could be reduced.

Gomez et al. (2006) used mass balance measurements to determine sugar losses at each process stage between harvesting and shredding at the mill. Comparative studies of a John Deere 3510 harvester in 2002 (fan speed 1250 rpm) harvesting in green and burnt cane showed that the extractor loss ranged between 8.7 % in green cane to 4 % in burnt cane of the total available sugar per hectare. The trials were repeated in 2005, with a similar John Deere 3510 (fan speed 900 rpm) harvester and extractor loss was measured at 3.4 % in green cane and 0.3 % in burnt cane of the total available sugar per hectare. They found a very high correlation between fan speed and cane loss and a very poor correlation between fan speed and EM (Figure 17).

Whiteing et al. (2002) found that the primary cleaning system removes about 30-60% of cane by weight of the total extracted material (Figure 18). Dick and Grevis-James (1992) and Whiteing et al. (2002) found that the secondary cleaning system removes about 20% of the EM presented to it and that it can also remove significant amounts of cane. The secondary extractor can remove over 100% of cane by weight of the total extracted material. That is over one kg of cane is removed for each kg of vegetative EM.
4.7 Benefits Delivered

Significant benefits to the Australian sugar industry have been delivered through understanding the nature of loss and quantifying the magnitude of loss of cane and sucrose. This has included:

- Developed and utilised direct measurement techniques to determine magnitude of cane loss. Total cane loss recorded from 1.1 to 8.5% (2.8 to 15.2%) from overseas and shown to underestimate the absolute magnitude of harvesting losses.

- Utilised indirect measurement techniques to determine an accurate absolute magnitude of loss for economic evaluation of harvesting. Total loss from indirect measurement found to range from 4.1% to 21.1%.

- Pre and post harvest sampling indicates that current harvesting technology is very inefficient in separating low CCS components (trash and tops) from millable cane. The extractor fan removes a significant volume of material from the cane supply with minimal impact on CCS indicating that the ‘green cane trash blanket’ does indeed contain significant amounts of cane and sugar juice.

- Quantified the nature of losses and demonstrated that the variability of cane loss depends on the circumstances. Losses from billeting and primary extractor are the main sources of loss.

- Highlighted the potential for extremely significant losses.

- Identified the drivers of losses and developed solutions which underpin the HBP guidelines (see section 5). For example optimising feed train/chopper relationship can reduce losses by up to 3%.
4.8 Research Opportunities

- Progress in harvester development depends on the reliability of performance testing. This includes cane and sucrose loss measurement, not only in test facilities, but also in the field.

- Method of testing – mass balance v direct methods should be standardised.

- Assessment of sucrose loss from machine process modifications in retro-fit developments and embodied in late model machines e.g. Anti-vortex fan, 12-blades per drum rotary-pinch chopper systems should be undertaken.

- Shortening billet length has shown to result in lower juice Brix and lower juice purity. This is an interesting result whose cause deserves further investigation.

- Finding an acceptable balance between billet length (sucrose loss) and bin density. The loss of sucrose mass and should be examined during short billet production.

- Continue support to develop a rapid in-field sucrose assessment method. Such a system would have a big impact on harvester performance assessments, fine tuning of machines and driving widespread adoption of HBP principles.

- Greater ownership of the magnitude of sugar losses
5  HARVESTING BEST PRACTICE (HBP)

Whiteing et al. (2001, 2002) and Agnew (2002) reported on a program aimed at increasing sugar industry profitability through harvesting best practice. Harvesting Best Practice (HBP) guidelines examine harvester set-up and operational settings, field conditions, farm layout, farm practice and their effect on harvester performance, cane quality, sugar quality and industry profitability.

HBP recommendations have been presented to the industry for a number of years. Despite the significant economic benefits, adoption of HBP has been slow due to industry scepticism about sugar loss levels and pressure to minimise extraneous matter and transport costs. The invisible nature of the sugar loss makes it difficult to convince some industry stakeholders of the importance of HBP.

In addition, it is also hard to encourage the adoption of HBP especially when it has long been recognised that the current one-price, dollar-per-tonne payment method for harvesting does not have built-in incentives to adopt best practice or supply quality cane. Better feedback is vital to overcome the flawed harvester-payment system and enable negotiation of the best possible job at an acceptable price for individual blocks.

It is also hard to encourage the adoption of HBP especially when figures on extraneous matter and bin weight are presented to operators on a daily basis while cane loss might be mentioned at a meeting once a year. A method to quickly and accurately measure cane loss directly from field residue samples would be a massive boost to the promotion and adoption of HBP to minimise sugar losses.

Issues underpinning HBP are now discussed.

5.1 Feed Train/Chopper Optimisation

Optimising the feed train/chopper system involves setting the surface speed of the feed train rollers to approximately 70% of the chopper tip speed. The speed at which the cane enters the feed train closely equates to typical forward speed of the harvester.

Case IH production standard harvesters with 15-inch chopper systems (assessed by BSES Limited in their feed train/chopper optimisation program) typically have a feed train/chopper ratio ranging from around 0.46 to 0.56 for ‘short’ and ‘long’ billet settings respectively (C Whiteing 2008 pers comm.). The ‘short’ billet setting in this harvester results in a feed train/chopper ratio is 0.52.

The John Deere 3500 series machines have a synchronised feed train/chopper setup although a pressure compensated flow control valve allows the feed train to be slowed to ‘shorten’ the billet length. This essentially reduces the feed train/chopper ratio.

Hockings et al. (2000) and Davis and Norris (2002) have demonstrated the benefits of reduced losses with a synchronised feed train/chopper system and the subsequent improvements to the flow of material through the feed train.
5.2 Extractor Loss and Extraneous Matter

5.2.1 Fanspeed

The existing practice of running high fan speeds to 'clean the cane' marginally reduces the EM processed at the mill, but this results in substantial cane loss. Figure 19 indicates that although increasing fanspeed improved CCS the significant increase in cane loss actually reduced grower and hence industry income. Hence, one of the integral components underpinning HBP is reducing cane loss, whilst maintaining or improving cane quality.

Figure 17 indicates that to minimise extractor losses operators should operate at the lower end of the fanspeed curve. This is the first component of best practice to reduce losses, but trial data suggests that, in order to maintain cane quality, pour rate and fanspeed need to be reduced simultaneously (Sandell and Agnew 2002).

![Fanspeed vs CCS & $/HA - Trial 9, 96 Cameco, Q152 badly lodged](image)

**FIGURE 19: EFFECT OF FAN SPEED ON CCS AND GROWER RETURNS (WHITEING 1997)**

5.2.2 Pour Rate

Pour rate is an important performance measure in any harvesting system. Pour rate is defined as how fast cane flows through the machine and is measured in tonnes per hour. Crop size and harvester forward speed determine pour rate. Pour rate is the instantaneous rate at which cane is leaving the elevator and is not the average delivery rate of the machine. For example, a harvester travelling at 7 km/h in a 100 t/ha crop has an instantaneous pour rate of 105 t/hr. After turning and waiting time is accounted for, this operation might deliver cane to the rail siding at 60 t/hr. This is the difference between instantaneous pour rate and delivery rate.
Under given field and crop conditions, harvester pour rate has a significant impact on the final trash levels in the harvested product (Figure 20) (Whiteing et al. 2002). Trash levels increase and CCS decrease as pour rate increases. These pour rate trials were conducted with fan speed and all other parameters kept constant, while ground speed was varied.

**Figure 20: Effect of Pour Rate on Trash and CCS Levels (Whiteing et al. 2002)**

Figure 21 shows the final trash levels of Q152 harvested at two pour rates. As pour rate is reduced, the layer of material passing through the machine becomes thinner, reducing the overload on the extractor system, thus improving cleaning performance. Whiteing et al. (2002) highlights the limitations of the current primary cleaning system to efficiently remove trash at high pour rates. While current machines have the power to process cane in excess of 150 t/hr, the cleaning system will only clean efficiently at less than half this rate. This mismatch makes the harvester operator’s job of producing a quality product at desired pour rates very difficult.
Whiteing et al. (2002) trials are summarised in Figure 22 to give a representation of harvester performance under typical conditions. At a given pour rate, extractor fan speed has limited impact on trash levels in the bin. Changing pour rate, however, causes significant changes in trash levels. Brazil and Argentina research data supports the work of Whiteing et al. (2002), indicating similar harvester performance characteristics.

Figure 19 indicates a small improvement in CCS as fanspeed increases due to the removal of a small amount of trash. However, the large increase in cane loss offsets any benefits from improved CCS and grower returns decrease with increasing fanspeed. This has proved the case in all fanspeed trials (Whiteing et al. 2002).
This shows that reducing pour rate is the best approach to improving quality. It should be noted that in some lodged crops where cane feed is erratic, reducing pour rate does not necessarily cause a significant reduction in EM levels.

It is the opinion of most operators that the cleaning system has the capacity to handle high pour rates and simply increasing fan speed was the solution to cleaning issues, not reducing throughput.

A comparison of HBP and ‘standard’ harvesting practice (at the time) conducted by Whiteing et al. (2002) in 1998 is shown in Table 3. Treatments included ‘standard’ (primary extractor at 1300 rpm and an instantaneous pour rate of 125 t/hr) and recommended best practice (Fan speed 100 rpm and pour rate of 100 t/hr).

This shows that cane quality improved slightly with best practice operation with trash decreasing by about 1% and the CCS being higher than ‘standard’ practice. However, the real improvement can be seen in the clean cane yield (total yield less EM), which increased from 138 t/ha to 149 t/ha. This significant reduction in cane loss, coupled with improved quality, resulted in an improvement in the grower’s income of over $200 per hectare.

### TABLE 3: COMPARISON OF HARVESTING BEST PRACTICE VERSUS ‘NORMAL’ OPERATION (WHITEING ET AL. 2002)

<table>
<thead>
<tr>
<th>Fan Speed and Pour Rate Trial – 97 Austoft 7000</th>
<th>Means</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground speed</td>
<td>Pour rate</td>
</tr>
<tr>
<td>km/h</td>
<td>t/hr</td>
</tr>
<tr>
<td>5.5</td>
<td>125</td>
</tr>
<tr>
<td>4</td>
<td>97</td>
</tr>
</tbody>
</table>

The sugar industry, especially growers and miller, would accrue substantial benefits if harvesting best practice were widely adopted. The major barrier to the adoption of this practice is the fixed price per tonne paid to harvester contractors, which is a disincentive to reduce pour rate. Although the operator benefits from reduced cane loss as he delivers more tonnes, there are additional costs associated with slowing the harvester down.

Reduced pour rate means more time spent in the field, thus increasing wages and fuel usage. This effectively reduces the operations hourly income.

Stainlay (unpublished) investigated the advantages of HBP through an assessment of a number of harvesting groups in Tully. Information on average row lengths, haul distances and machinery types and combinations of harvester pour rate were modelled to examine the impacts on harvest cost, day length and cane quality. The modelling indicated that harvesting costs would increase under HBP operation. Table 4 shows one scenario which highlight the barrier to HBP adoption created by the flat rate ($/tonne) paid for harvesting. The increased yield under best practice operation increases the harvester’s earnings per hectare but the additional fuel and labour costs actually reduce the hourly income of the machine.
TABLE 4: PAYMENT CALCULATIONS FROM A HBP TRIAL (STAINLAY, UNPUBLISHED)

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Best practice</th>
<th>Standard operation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Payment Calculations</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CCS</td>
<td>14.96</td>
<td>14.8</td>
</tr>
<tr>
<td>Yield tonnes/ha</td>
<td>80</td>
<td>74</td>
</tr>
<tr>
<td>Grower fibre</td>
<td>15.7</td>
<td>15.6</td>
</tr>
<tr>
<td><strong>Industry Return $/ha</strong></td>
<td><strong>$2 529</strong></td>
<td><strong>$2 322</strong></td>
</tr>
<tr>
<td>Growers Return $/ha</td>
<td>$1 332</td>
<td>$1 213</td>
</tr>
<tr>
<td>Harvester $/ha</td>
<td>$478</td>
<td>$443</td>
</tr>
<tr>
<td>Mill return $/ha</td>
<td>$719</td>
<td>$666</td>
</tr>
<tr>
<td><strong>Trial harvest efficiency</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Machine Efficiency</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yield tonnes/ha</td>
<td>80</td>
<td>74</td>
</tr>
<tr>
<td>Actual cutting time (min)</td>
<td>32</td>
<td>30</td>
</tr>
<tr>
<td>Total harvest time (min)</td>
<td>46</td>
<td>44</td>
</tr>
<tr>
<td>Harvest efficiency %</td>
<td>71</td>
<td>69</td>
</tr>
<tr>
<td>Harvester engine hours</td>
<td>0.8</td>
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<tr>
<td>Harvester tonnes/engine hour</td>
<td>53</td>
<td>59</td>
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<tr>
<td>Harvester fuel/treatment</td>
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<tr>
<td>Harvester fuel use g L/tonne</td>
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<tr>
<td>Engine (h/ha)</td>
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<td>1.2</td>
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<tr>
<td><strong>Harvester $/ha</strong></td>
<td><strong>$478</strong></td>
<td><strong>$443</strong></td>
</tr>
<tr>
<td><strong>Harvester $/h</strong></td>
<td><strong>$334</strong></td>
<td><strong>$360</strong></td>
</tr>
<tr>
<td>Average bin weight</td>
<td>6.5</td>
<td>6.9</td>
</tr>
<tr>
<td>Haul trips/ha</td>
<td>12.3</td>
<td>10.8</td>
</tr>
<tr>
<td>Average haul weight</td>
<td>6.5</td>
<td>6.8</td>
</tr>
</tbody>
</table>

McDonald et al. (2003) undertook a series of trials to gain a better understanding of the costs and benefits of HBP in green and burnt cane in the Burdekin and Herbert regions. They assessed different combinations of harvester ground speed, thus pour rate and primary extractor speeds. In green cane trials they found that increasing fan speed above 900 rpm did not increase CCS. As pour rate increased, so did EM and sugar yields. They hypothesised that the sugar transferred onto trash is retained at higher pour rates (with increased EM).

In green cane trials reducing pour rate and fan speed resulted in an increase in grower income. At a pour rate of 150 t/hr, and reducing fan speed from 1100 to 800 rpm increased return to the grower by 5%. At a pour rate of 80 t/hr, reducing fan speed from 100 to 800 rpm increased return to the grower of 8.5%. In burnt cane trials, the no fans treatments maximised the returns to growers by 1.2% to 7.8% (McDonald et al. 2003). These results support the work of Whiteing et al. (2002).

The higher pour rates combined with low fan speeds reduced bin weights. The effect of EM on bin weights has been identified previously. Shaw and Brotherton (1992) found that for every 1% increase in EM, bin weights were reduced by 0.1 tonnes. Pope (1998) found a significant relationship between EM and bin weight at Mulgrave Mill where a 5% increase in EM resulted in a 0.1–0.2 tonne decrease in bin weight (for 4 tonne bins).
The impacts of EM on milling profitability are significant. Reduced bin weights decrease the amount of cane that can be transported to the mill with a given number of bins. This could increase capital costs for a mill and slow crushing rates (Kent et al. 1999) and as a result, increase season length. Excessive EM can also reduce the recovery of sugar (Kent et al. 1999).

Gomez et al. (2006) investigated losses from green and burnt cane at Ledesma mill in Argentina. They found that losses in the green cane harvesting trials were mainly due to the primary extractor and trash. Therefore, at Ledesma they moved to reduce fan speeds from 1250 to 900 rpm for harvesters fitted with 1.5m diameter fans. They are now looking at further reducing fan speeds and lowering their pour rate in an attempt to reduce extractor losses and EM levels when harvesting green cane.

On an industry-wide scale, HBP appears to be cost effective. However, HBP involves slowing harvester speeds to reduce pour rates and therefore can lead to increased harvesting costs. Benefits from HBP are likely to accrue to growers and millers through increased yields (due to reduced losses) and increased CCS and lower bin weights (through reduced EM). In addition, growers are reluctant to take the next step of paying more to earn more, possibly because of the difficulty in assessing whether or not the harvester was operated at best practice.

One way to address this conflict is to design a payment system that accounts for the extra costs incurred by harvester operators. Substantial negotiation would be required before a new payment system could be implemented. Thus, it is important that the benefits achievable from HBP operation and the costs incurred by harvester operators are clearly defined.

5.2.3 Payment Systems

One of the market impediments hindering the adoption of best practice for harvesting is the one-price, dollar-per-tonne payment method for harvesting. It provides no incentive for growers to improve farm layout or presentation for harvest, because the same price is paid for harvesting under all conditions. Harvester operators do have an incentive to reduce cane loss. However, they have no incentive to reduce extraneous matter and soil in the cane supply (Willcox et al. 2004).

The simple one-price system paid for harvesting has been recognised for some time as a barrier to the adoption of best-practice farming for harvesting. Ridge et al. (1996) developed a harvest-transport model to predict throughput and costs for particular field conditions. The model has been used as an aid in determining prices for contract harvesting.

Chapman and Grevis-James (1998) examined options for a charging formula for harvesting of cane within a harvesting cooperative in New South Wales. They assessed options including the flat-rate tonnage method, an hourly rate, and a combined flat/hourly rate. They showed that the concept of a differential rate of charging for harvesting has advantages and disadvantages. The barriers to adoption included compensation for wet weather and distance to receival pads; the process was viewed as a threat to the philosophy of equality among members; human error in clocking on and off; reliability of hardware and software; servicing of equipment problems due to remote locations; data verification was too time consuming. The cooperative did not adopt the new system.
The use of a simple logbook system to analyse the differences in harvesting productivity among blocks and farms was advocated by Powell et al. (2001). They noted that the current system of planning a harvest at group level and applying an average harvest daily allotment and charging a flat rate per tonne may not facilitate best-practice harvesting. They suggested a system that cane-quality measurement at the mill with HBP to provide incentives for supplying quality cane.

Increasing sugar industry profitability through harvesting best practice has been investigated by Agnew et al. (2002) and Agnew (2002). They noted that timely and accurate feedback is required to overcome the existing harvester-payment system and enable negotiation of the best possible job at an acceptable price for individual blocks. The timeliness of feedback will be improved to all participants with the use of NIR at mills to determine individual fibre and other quality parameters. The use of harvest plans must be an integral part of the package.

The timeliness of feedback has been explored by Mackay Sugar using a web based system (Markley et al. 2003, Markley et al. 2006, Markley et al. 2008). The recording of information on location and operational settings of harvesters is undertaken using a real time monitoring system - MTData.

The use of on-line cane analysis by NIR spectroscopy was described by Staunton et al. (1999). Results showed that NIR fibre is a more meaningful estimate of individual rake fibre than that supplied by class fibre, and the system provided information to assist growers and contractors in managing their operations. NIR was shown to be an accurate measure for juice brix, juice polarisation, CCS, water, ash, Pol in open cells, inorganic substances and extraneous matter.

Staunton et al. (1999) has used NIR to measure several cane-quality parameters, such as sucrose, impurities, fibre, ash, dry matter and to develop a Cane Quality Index. This method of determining cane quality has many potential benefits. These include as a benchmarking tool for productivity, adjusting cane payment using a cane quality bonus/penalty scheme with the current payment system and as quality index in a new payment system.

Use of NIR to measure cane quality to provide clear market signals is viewed as a critical step in achieving best-practice harvesting. NIR is currently used by Maryborough Sugar (Maryborough Mill, Mulgrave Mill), Mossman Mill, Mackay Sugar (Racecourse, Marian, Farleigh), Tully Sugar Mill, Isis Central Mill, NSW Sugar Milling Co-op (Condong, Broadwater, Harwood), Rocky Point, Bundaberg Sugar (Tableiland, Millaquin).

Optimal harvest structures and policies that increase whole-of industry profitability through the establishment of meaningful pricing structures that reflect quality of work and output, and that improve efficiency and market satisfaction have been investigated by Willcox et al. (2004) and Willcox et al. (2005).

They found that the current flat rate ($/t) system encourages maximum efficiency in terms of maintaining a high delivery rate. It encourages minimal loss, because every lost tonne is lost income (however, some losses are incurred in the pursuit of maximising output). However, it is easy to monitor and understand, but sends a very clear market signal that tonnes per hour equals dollars per hour and quality is a minor focus (especially since growers are more likely to change operator for pricing reasons rather than job-quality issues).

Willcox et al. (2005) identified a number of alternative payment methods including:
**a) Base Rate plus Fuel (BR+F).** This method is widely used at Maryborough. There, the base rate varies between $5.50 and $5.80 per tonne depending whether burnt or green. The fuel is paid for by the grower but delivered to the contractor's tank. The system is easy to monitor and 'police', because it is a simple system. It is fair, because the grower pays for fuel actually used on the farm. It does reduce the level of cross subsidisation, but still puts the cost of bad blocks back onto the harvester. BR+F still sends the market signal for high pour rates to maintain viability, but not as much as $/tonne. The system is commercially proven in Maryborough (Willcox et al. 2005).

**b) Base Rate plus Fuel at higher rate.** This method uses a base rate but the fuel is priced higher (e.g. $2/L) to allow for labour. The system is used by some groups in New South Wales. The amount of fuel used is measured and the grower invoiced at set price. The reasoning behind this system is that paying for fuel alone does not compensate for machinery and labour costs.

**c) Hourly Rate.** This method pays on engine hours similar to the hire of most earthmoving equipment and is negotiated between grower and contractor. Rates used for pilot group examples were $350-420/hour, depending on the number and size of haulouts. For acceptance, monitoring equipment is needed for growers to know that the machine was working as contracted, e.g. fan speed, forward speed, GPS tracking. Hourly Rate sends the best market signals, as it creates the greatest variation in price per tonne and reflects true cost, as most variable costs are accumulated on an hourly basis. This encourages best-practice farming, as the more efficient a farm is to harvest and the better the crop size and yield, the lower the cost per tonne to harvest. By providing a stable income to the operator, it allows the grower to prescribe the mode of harvester operation for each block. If a grower does not understand the financial benefits of HBP, this could lead to unwise decision-making focused on minimum time and, hence, minimum cost at the expense of high cane loss, low cane quality and poor ratoons. To operate efficiently, hourly rate needs to be linked to a cane quality measurement system at the mill to provide targets for cane quality. In addition, there is no incentive for the harvester to reduce cane loss, so settings of the harvester, such as extractor fan speed and forward speed, need to be monitored (Willcox et al. 2005).

**d) Sliding-Scale Base Rate plus Fuel.** This method uses a sliding scale based on crop yield to calculate a base rate, e.g. $6.30 for 35-45 t/ha to $5.70 for 95-105 t/ha. Fuel is purchased by the grower. This appears a simple system with good market signals. It is transparent and easy to apply. The base rate covers cane loss issues and true fuel costs are covered. The sliding scale covers some of the labour and machinery costs associated with crop size. It reflects true cost a little better, but is still a tonnage rate, which encourages maximising pour rate and delivery rate (Willcox et al. 2005).

### 5.3 Benefits Delivered

A demonstrated increase in sugar industry profitability has been the benefit delivered to the Australian sugar industry through an understanding of the interactions and relationships between harvester set-up and operational settings, field conditions, farm layout, farm practice and their effect on harvester performance, cane quality, sugar quality and industry profitability. This has resulted in the development of HBP guidelines. Benefits delivered include:
• Techniques for minimising losses from chopper systems and primary cleaning systems and minimising EM have been delivered to the industry.

• The industry has recognised that current payment systems do not have built-in incentives to adopt best practice or supply quality cane. Alternative cane payment structures that reflect quality of work and output have been investigated and are being implemented across the industry.

• HBP has shown that industry profitability can be significantly increased without capital investment through reduction in field losses of cane and juice during harvesting.

5.4 Research Opportunities

• Adoption of HBP has been slow due to industry skepticism about sugar loss levels and pressure to minimise extraneous matter and transport costs. The invisible nature of the sugar loss makes it difficult to convince some industry stakeholders of the importance of HBP.

• HBP should be a priority for the industry as the benefits have been defined. However, educating the industry with respect to the drivers of HBP e.g. cleaning system performance – fan speed and pour rate is a priority.

• The benefits achievable from HBP operation and the costs incurred by harvester operators need to be clearly defined.

• Real-time and accurate feedback is required to overcome the existing harvester-payment system and enable negotiation of the best possible job at an acceptable price for individual blocks.

• A method to quickly and accurately measure cane loss directly from field residue samples would be a massive boost to the promotion and adoption of HBP to minimise sugar losses.

• Value chain modelling to demonstrate impact of HBP on alternative harvesting systems (e.g. whole-of-crop harvesting) should also being supported.
6 HARVESTER PERFORMANCE MONITORING

The manufacturers approach to performance monitoring of cane harvesters during harvesting has been to provide only the condition analysis of the mechanical components such as the engine and hydraulic circuitry. For example engine hours, engine speed, oil temp and hydraulic oil level, temperature and component pressures (chopper, basecutter, feed train) are available. The only condition reported on performance with respect to machine-crop interaction is basecutter height and primary extractor fan speed.

Hildebrand (2002) viewed recovery of any substantial loss of sugar in the field during harvest as being the most obvious and potentially the least costly economic gain available. Therefore, a major opportunity for the sugar industry is to significantly increase industry profitability without increased capital investment. This can be achieved by reducing field losses of cane and juice during mechanical harvesting. Adopting HBP with attention to extractor fan speed, pour rate, feed train and chopper speed synchronisation, basecutter height control and row profile, row length and cane presentation has two main outcomes. It increases the amount of cane delivered to mills and reduces the potential for environmental impacts associated with sugar juice entering waterways causing de-oxygenation (SRDC 2004).

Benchmarking of Australian harvesting operations against Brazilian mechanical harvesting operations has been undertaken by Agnew (2002) and Powell et al. (2001). It is apparent from this that Brazilian operations have higher field efficiencies than the average in the Australian industry.

Measuring field and other variables affecting machine performance is necessary to encourage more efficient harvesting, reducing costs and increase industry profitability through reducing field losses of cane and juice during mechanical harvesting.

Agnew (2002) reported that better and more timely feedback is vital to overcome the flawed harvester-payment system and enable negotiation of the best possible job at an acceptable price for individual blocks.

Various technologies have been researched and developed to provide machine performance feedback or automate machine operations to favour higher harvesting efficiency and higher sugar recovery. These include automatic basecutter height control, synchronising component speed with ground speed, cane loss monitoring, ground speed and pour rate monitoring, harvester efficiency and cane yield monitoring. The aim of these technologies is to optimise on-the-go, the interaction between machine components and the crop. This will transfer as much of the sugar standing in the field to the mill, whilst minimising extraneous matter (EM) and dirt in the supply.

Recent developments in harvester monitoring and performance (Section 6.1.5) have seen the mounting on harvesters of various system configurations, that incorporate sensors to allow the status of the machine to be determined. These systems typically monitor elevator on/off and engine on/off and incorporate GPS to allow tracking and harvester ‘state’ to be defined. Recently, these systems have been expanded to include additional sensors to monitor harvester components including chopper pressure, feed train roller pressure, feed train roller opening and elevator pressure. The specific purpose of the additional sensors is to collect data to allow estimation of harvest yield.
6.1 Real-Time Monitoring Systems

6.1.1 Basecutter Height Control

The basecutter height setting is crucial for effective gathering of cane, minimisation of stool damage and reduction of soil intake. Improper adjustment of the basecutter height during harvesting affects both the quality of cane supplied to the mill and the remaining stool. Henkel et al. (1979) found that the height of the basecutter relative to the ground had an effect on the amount of dirt entering the cane supply, whilst Kent et al. (1999) demonstrated that, during the raw sugar refining process, CCS is degraded in proportion to the percentage of dirt in the harvested cane.

Due to the position of the harvester cabin on standard ‘chopped cane’ harvesters, the operator cannot see where the basecutter is actually cutting. This results in the optimum height seldom being achieved during operation. The operator sets the basecutter height using a sight gauge in the cabin and this system offers no direct feedback to the operator on the appropriateness of the basecutter height to the desired height. It appears that most operators adjust the basecutter based on experience and through a combination of visual inspection of the row profile behind the harvester and by observing the basecutter pressure reading (Woods and Schembri 2002). The operator is not capable of maintaining the optimum height whilst traversing uneven terrain (Woods and Schembri 2002).

The development of automatic basecutter height control systems has occurred with systems that rely on interaction with the soil to gauge basecutter height (mechanical contact), non-soil contact or ground height sensing methods or a combination of both (Wood and Schembri 2002).

*Mechanical Contact Sensors*

Mechanical contact sensors measure the ground height using a skid or wheel. The main problems with this type of sensor is the interference from trash, mud and/or cane itself in that it is often caught in the device causing jamming of the mechanical movement.

Monitoring of hydraulic pressure across the hydraulically driven basecutter motor has been investigated as one approach at controlling basecutter height. In theory, the pressure should vary as the basecutter starts to cut more deeply into the more dense ground. Reidenbach et al. (1979) demonstrated that basecutter pressure is impacted on by both depth of operation below the soil surface and by material flow rate across the basecutters (pour rate). They hypothesised that for basecutter pressure to be used as a viable system for basecutter height control, compensation for pour rate and probably forward speed would be essential.

In this situation, the basecutter essentially becomes the mechanical contact. Musumeci (1983) and Garson (1992) investigated basecutter height control systems using variations in the torque in the basecutter drive as a measure of the basecutter height. The results indicated that the fluctuation in basecutter pressure varied non-linearly with both the cutting height and the harvesters travel speed making it difficult to use this method with any confidence. As a consequence no further industry research has occurred on this technique.
A mechanical height control system has been developed by the Copersucar Technology Center in Brazil, which utilises a floating basecutter arrangement with a raised dome hubcap below the disks to raise the blade height when the ground level increases (Neves et al. 2001). In this system, the basecutter arrangement movement was independent of the harvester mainframe. This system measures behind the basecutter, which is less desirable from a control viewpoint. Field trials showed a 50% reduction in soil level in the cane supply and 50% more stubble remaining in the field when the floating system was used as opposed to the conventional fixed system. Blade wear was also reduced by 2.5 times on the floating system. Currently there are 133 harvesters at 33 mills fitted with the CTC floating basecutter. Due to patent rights, the Copersucar version is not available outside of Brazil.

Case IH Austoft manufactured a floating basecutter which operated on the same principle as the Copersucar floating basecutter, but the mechanical set-up was slightly different. The system was installed on the 2002 Case IH Austoft production prototype and underwent commercial evaluation in Australia. However, problems with matching hubcap shape to row profile and hubcap wear were experienced. One production harvester was sold in 2003 with the floating basecutter. However, due to further problems with ground following ability in heavy red soil, the floating capability was disabled.

Non-Contact Sensors

This type of sensor attempts to determine the ground position by detecting changes in an electromagnetic field or a travelling wave that interacts with the ground. Two sensors of this type that have been investigated are ultrasonic sensors that measure delays to a sound wave, and radar sensor that detect variations in a travelling electromagnetic wave.

Garson (1992) investigated the use of sensors that transmit an ultrasonic signal and is subsequently reflected by the ground. The advantage of an ultrasonic system was that the control system is no longer dependent on soil conditions, a feature which has always confounded mechanical/hydraulic systems. In this approach, two ultrasonic sensors were mounted in the throat of the harvester 1.2 m ahead of the basecutters and 0.7 m above the ground. This system performed well in burnt cane, but the interference of trash and green leaves in green cane detracted from the usefulness of the system (Garson and Armstrong 1993).

Sam and Ridd (1996) attempted to overcome the line of sight deficiency with the ultrasonic system by using electromagnetic induction technology, but the technique proved to lack the required height resolution.

Schembri et al. (2000) advanced the use of ultrasonic sensors by allowing this technology to be used in green cane harvesting. They positioned the sensors on the outside of the harvester throat and slightly ahead of the basecutters. In this position, the sensors were protected from the cane, leaf and trash, which are processed through the harvester throat. The crop divider shoes plus the internal floating walls acted to direct the trash and leaf into the basecutters and away from the paths of the height sensing ultrasonic transducers. The transducers were coupled to a commercial controller that compared the average height recorded by these sensors with a set point and adjusted the harvester height to maintain the set point. This system advanced the use of ultrasonic sensors by allowing them to be used in burnt and green cane harvesting conditions. However, the system was unable to
automatically detect the top of the stool and it did not maintain correct base-cutter heights whenever significant changes in stool profile were experienced.

The height-control system can be fitted to any harvester, or installed into the production machines. Currently, this system is in the process of being quantified in terms of the industry benefits, that is lower dirt levels in the cane supply and reduced cane loss in the field. Evidence of improvements in dirt and cane-loss levels is essential for the up-take of this technology by the harvesting sector. This system is not commercially available to date.

Work by Woods and Schembri (2002) investigated the use of electromagnetic waves (microwaves) for detecting the ground surface. Microwaves will penetrate most materials to differing degrees and, therefore, has a potential for use on a harvester in front of the basecutters to sense the ground and form the basis of a system to control basecutter height. This work paralleled the development of the ultrasonic sensor described above. The optimum frequency range and polarisation state of a microwave sensor to measure ground level through cane was determined and a prototype microwave ground detection system, which can operate under harvesting conditions, was developed. The detection system was fitted to a harvester and field evaluation completed. The sensor performed as expected, however, the interpretation of results was limited due to the problem of not having an independent measure of ground height. The project developed the foundations of a microwave ground detection sensor, although the complete dynamic operational characteristics were not evaluated (Woods and Schembri 2002). No further work progressing the development of this type of sensor has occurred.

Schembri (2002) and Schembri et al. (2000) developed a basecutter height control system which used two ultrasonic sensors to provide ground height measurements (one sensor either side of the base cutters). The electronic controller raised or lowered the harvester base cutters until the measured height equaled the set height for the base cutters. This system known as the SRI system was developed to the pre-production prototype stage by CNH Austoft. The limitation of these types of systems are that due to the basecutters being fixed to the harvester frame, adjusting the height of the basecutters involves raising and lowering the entire harvester frame.

Schembri et al. (2004) compared the SRI automatic basecutter height control system and the CNH Austoft floating basecutter arrangement. They found that for the conditions under which the trials were conducted, both height control systems reduced the amount of dirt in the cane supply as compared to manual height control. The floating base cutters reduced ash-in-cane compared to manual control by 20%, while the SRI system lowered ash-in-cane (compared to manual control) by 11% (although this result was not statistically significant). The reduction in dirt for both systems was achieved with an increase in cane loss, although the magnitudes of the increases in cane loss were relatively small.

Recent developments in automatic basecutter height control have been based on monitoring basecutter hydraulic pressure. The advantage of this approach is that it is relatively simple and robust. However, the non-linear fluctuation in basecutter pressure with both the cutting height and the harvesters travel speed makes it difficult to use this method with any confidence.

Esquivel et al. (2003) developed a system for automatic control of the basecutter system and forward speed in a Cuban harvester KTP-3S (Hernández et al. 2000). This system is in use in Brazil and Australia. The system measures basecutter pressure with minimum and maximum base cutter pressures initially set for specific field characteristics (e.g. soil type,
cane variety, crop type). An algorithm processes the data from the sensor and adjusts automatically the base cut height, according to initial settings.

The evaluation of the automatic base cutter system performed in 2002 in São Martinho Mill, São Paulo, demonstrated a reduction in harvest base cutter losses by cut height of up to 88%, increasing the amount of cane harvested by 990 kg/ha (TechAgro 2002). This system has been installed on 4 machines in the Herbert and field trials were conducted during the 2007 and 2008 harvest seasons. There has been a varied response from industry with the main issues relating to modified hydraulic systems and response time due to the speed of machine operation being about double that of machines in Brazil (LP Dibella 2009 pers comm.). No further performance details are available.

The cost of the TechAgro system is between $12,000 and $14,000 AUD (depending on exchange rates), including 1 year warranty, and technical support negotiated.

CASE IH has developed a new basecutter automatic height control system, the AUTO TRACKER. The AUTO TRACKER can be retrofitted to existing track (CASE IH A7700) and wheeled harvesters (CASE IH A7000) and from January 2006, was being offered for new model harvesters.

The operation of the AUTO TRACKER is based on monitoring the basecutter hydraulic pressure associated to the maximum and minimum height space in relation to the ground, the response time, and other operational information, which make the system react according to the harvest location requirements. The advantage of the AUTO TRACKER system when compared with the TechAgro system is that it provides positional feedback and preset height positions can be set. The cost of the AUTOTRACKER is around $15,000.

![FIGURE 23: TECHAGRO ONBOARD COMPUTER SYSTEM FOR AUTOMATIC BASECUTTER HEIGHT CONTROL](image)
Both systems claim a reduction in cane loss and dirt, with the AUTOTRACKER a reduction of cane loss (stumps bound to the rootstalk) of around 720kg/ha and the TechAgro system claim a 50% reduction in stubble remaining when compared with conventional systems.

The performance of pressure based systems under Australian conditions (e.g. lodged cane, machine speed) will need to be quantified.

6.1.2 Cane-Loss Monitor

Hurney et al. (1984) found that a high proportion of cane loss occurs in the primary extractor where cane pieces can be blown out with the extraneous matter. The impact of cane billets can be heard clearly, and it was thought feasible to develop an instrument that emulated this observation using some form of acoustic technique (Dick et al. 1991). They tested various configurations of acoustic sensors, including microphones and piezo-electric sensors that produced signals allowing discrimination between billet impacts on the extractor shroud and other noises.

Dick and Grevis-James (1992) developed a cane loss monitor which detected vibrations in the primary extractor shroud to differentiate between impacts of billets and tops. As part of this system, ground speed, extractor fan speed, basecutter and chopper speed were monitored and displayed on an in-cab display. This was the first attempt at providing feedback on machine performance to the operator. However this information was not logged.
The system was commercialised by the company Agridry Rimik Pty Ltd and the system was based on the principle that the impact of billets on the primary extractor hood can be detected clearly and distinguished from other noise sources.

Dick et al. (1991) conducted a number of static trials, where a known mass of cane and extraneous matter were fed into the harvester, to compare integrated voltage from the cane loss sensor with mass balance derived losses. These trials showed a good correlation between cane-loss monitor reading and extractor losses (Dick et al. 1991).

Field trials conducted by Dick and Grevis-James (1992) showed the extractor hood cane loss monitor gave a good indication of relative cane loss. Calibration of the sensor was achieved by adjustment of a potentiometer when a known number of billets were thrown into the extraction chamber, or by applying a standard impact to the side of the hood (Agridry Rimik 1992). Calibration was based on the number of counts measured by the sensor, relative to number of billets. A closed loop control system was used with the nominal cane loss level fed back to automatically control fan speed (DR Ridge pers comm.)

The system, once calibrated for an individual harvester, provided the operator with a continuous indication of relative levels of cane loss per unit area. The system was commercialised with a number of units sold into the market.

The hood based system thus relied on discerning billets hitting the hood (hoods were fabricated from steel during this period). This system achieved reasonable accuracy under defined conditions, but appeared to lose the ability to accurately discern billet impact at high pour rates and was not as successful when fitted to the now industry standard plastic hood (Sandell and Agnew 2002). The system was able to measure only relative changes in cane loss and required frequent calibration. Furthermore, analysis of the trash blanket shows that the fan blades shred nearly all billets, making it difficult for the sensor to discern cane from trash (Sandell and Agnew 2002). The ability of the sensor to discern billet hits on the extractor hood, especially during high pour rates, is highly questionable. The robustness of the system (wiring sensors etc) also limited its adoption. There are no units currently in operation.

Alternative methods of sensing cane loss from the extractor were investigated by McCarthy et al. (2002). They measured the vibrations produced by billet impacts on the blades of the primary extractor fan. Thus, the fan blades replaced the extractor hood as the sensor location to detect cane billets passing through the extractor with the resulting output of hit counts providing a relative index of cane loss.

Whiteing et al. (2004) compared the performance of the hood and fan mounted sensors and investigated alternative methods for sensor calibration. Their study showed that both the hood and fan sensor were unable to distinguish actual billet hits and no relationship could be found linking sensor signal output to number of billet hits. Signal response to trash and tops dominates response due to cane billets. The study has, however, shown that both systems predict mass material flow and therefore cane loss through the extractor fan very well. This is because both sensors give a good measurement of total cane and trash flow through the primary extractor and cane loss is directly related to this total material flow. Calibrating the cane loss monitor by identifying ‘billet hits’ from the monitor when billets are thrown at the hood, which has previously been recommended, is not considered a good procedure. Derivation of a calibration equation based on an integration of sensor signal over time is considered more appropriate.
Currently there is no commercial product available to provide feedback to the operator on material flow through the extractor.

TechAgro is investigating an alternative approach whereby volumetric flow is used as an indicator of the cleaning efficiency with fan speed adjusted in proportion to material flow. This technology would form an integral component of a harvester performance monitoring system and would provide an opportunity for the industry to significantly increase the adoption of best practice harvesting.
6.1.3 Cane-Yield Monitoring

Real-time yield monitors have been developed for grain, cotton, horticultural and forage crops and are designed to record the harvested portion of a crop. Grain yield monitors were released commercially onto the global harvester market in the mid-1990s and have been a standard attachment to 90% of combine harvesting machines sold in Australia since 2000.

A number of different mass flow rate sensors have been developed for yield monitoring various crops. The methods used are mixed, ranging from direct mass measurements to indirect measurements of the power required to process the crop material. The development of a yield monitor for sugarcane has lagged behind that of other crops, in particular grain and cotton, due primarily to the nature of the product.

Cox (2002) showed that the basic technology is available for yield monitoring of sugarcane, with the exception of the mass flow rate sensor. Cox (2002) examined the functional and performance requirements of a mass flow rate sensor for sugarcane and examined four sensing techniques that appeared to offer a solution to the requirements:

1. Chopper Power Measurement - Uses the hydraulic power required to chop the sugarcane into billets as an indicator of the mass flow rate.
2. Elevator Power Measurement - Uses the hydraulic power required to elevate the billeted sugarcane into the ‘haul-out’ vehicle as an indicator of the mass flow rate.
3. Volumetric Measurement - Uses the separation distance between the feed rollers of the harvester feed train as a volumetric indicator of the mass flow rate.
4. Mass Measurement - Involves weighing the cane flow through the elevator of the harvester as it passes over a weighing platform defined as the ‘weigh pad’.

Cox (2002) evaluated the four techniques simultaneously by placing various sensors on a single harvester and comparing the sensor outputs with the mass flow rate as measured by a weigh truck. Cox (2002) found that each technique had potential, but also inherent problems and limitations.

Cox (2002) reported that the mass measurement technique, known as the ‘weigh pad’, offered the most potential for improvement and potential to accurately measure the mass flow rate with a single calibration under all conditions when compared to the indirect mass flow rate methods.

Cox (2002) developed a ‘weigh pad’ which consisted of a plate mounted in the elevator floor, hinged at one end and supported with two load cells on the other end. An accelerometer was included to measure the dynamics of this system, with the potential to improve the mass flow rate measurements.

The system, developed by Cox (2002) was patented in 1999 (Cox et al. 1999) and was commercialised by Case IH Austoft in 2000 and developed to pre-production prototype stage.

Many efforts have been made to develop yield monitors similar to Cox et al. (1999). These include Pierossi and Hassuani 1997; Pagnano and Magalhães 2001; Wendte et al. 2001; Benjamin et al. 2001; Molin and Menegatti 2004; Domingos and Magalhães 2005. These are described in Davis et al. (2007), with most remaining as prototypes.
Case IH are continuing to conduct research and develop the system developed by Cox et al. (1999) and aim to release a production retrofit yield mapping system in 2009 (Mal Baker, Case IH 2008 pers comm.).

In 2005 and 2006, Mackay Sugar has incorporated additional sensors into a number of harvester monitoring systems with the purpose of investigating the use of chopper box hydraulic pressure to estimate yield variation across a block. Analysis of these results is continuing (J Markley pers comm. 2008). A similar system marketed by Trimble is in use in the Burdekin region.

A cane flow monitor was developed by Hernández et al. (2003 a, b) and used as the basis of a yield monitor. Esquivel et al (2007) evaluated the yield monitor in a series of trials in 2007 and 2008 at Ingham. Preliminary results indicate a strong relationship between calculated and real weights ($R^2=0.91$).

**Figure 25: Pressure Transducer to Monitor Chopper Pressure (Left) and LVDT to Measure Feed Train Roller Displacement (Right).**

The enormous variability of the cane cropping environment (such as variety, class etc) and machine operational factors (such as chopper speed, blade wear, chain wear, mud build up on elevators, inconsistent feeding, extractor performance etc) makes the accurate calibration of indirect measurements such as chopper and elevator power and feed roller displacement very difficult. The most recent attempts at using these methods for yield estimation only utilise hydraulic pressures, not power.

Therefore, at best, these methods only offer a relative measurement of yield across a block and ideally should be used in combination with each other and pressure measurement extended to power. The advantage of these methods lies in their sensor simplicity, ease of installation and cost.

Bramley et al. (2008) is currently evaluating the three yield monitoring concepts currently available commercially in the Australian sugar industry. They found significant variation (disagreement) between yield monitors and identified the need for sugarcane yield monitoring to be done with differentially corrected GPS as opposed to standard GPS (as is generally used at present). These systems may also be used as a surrogate evaluation of machine performance e.g. pour rate.
6.1.4 Sugar-Yield Monitoring

Traditionally, the grower conducts static measurements of sugar concentration in the field with a handheld refractometer. More accurate measurements are later conducted at the mill using polarimetry and NIR techniques. These methods are the most popular because of their simplicity and accuracy. To date there has not been a method developed to reliably measure sugar concentration in real time that may be applied to the harvesting process.

The North Dakota State University has developed technology for an on-the-go sensor for determining the sugar content of an agricultural product, such as sugar beet, during harvesting or at other times. The machine combines NIR technology and statistical software to provide a faster, portable method of sugar content analysis. The sensor is coupled to a harvester/defoliator and uses a knife to slice a cross-section from the crown of the sugar beet during harvesting. This system has been patented (U.S. Patent No. 6,624,888) in 2005 and is commercially available (Panigrahi and Hofman 2003).

McCarthy and Billingsley (2002) developed a robust low cost refractometer together with signal conditioning algorithms to enable sucrose content to be measured during harvesting. This technology was applied to the topping mechanism to assist the harvester operator to top the cane at the optimum cutting height. This system included the development of a mechanised crushing device to squeeze the tops of the cane stalks to provide sufficient sample medium to the sensitive surface of the refractometer. The device was mounted on the topper arm directly behind the topper (Figure 26). In field evaluation, this method accurately and reliably measured sugar concentration at the top of the cane stalks in real-time during the harvesting process (McCarthy and Billingsley 2002). To date this technology is not commercially available.

The application of this technology for controlling topper height or by providing necessary relevant information to the harvester operator as an aid for maximising cane supply and to reduce sugar losses and the transfer of sugar on tops/trash from an environmental perspective may be an opportunity. This may be useful as an indicator of damage on other areas of the machine e.g. chopper system, cleaning chamber.

A technique to reliably measure sugar concentration in real time that may be applied to the harvesting process is an important consideration for the industry. This is a logical extension to the work by Doherty et al. (2007) and Sichter et al. (2005).
Current studies (Sichter et al. 2005, Doherty et al. 2007) are aimed at developing a reliable in-field technique for measuring sugar juice on trash. The potential of this technique, if proved to be reliable, for the monitoring of sugar yield in real-time should also be investigated.

6.1.5 Harvester Performance Monitoring

There have been a number of studies investigating harvesting efficiency as a result of rising harvest input costs such as capital, labour, parts and fuel. Whilst these are largely beyond the control of the industry measuring, maintaining and improving harvester productivity is the key to cost management.

Initial harvesting efficiency investigations involved manually recording a number of parameters such as fuel usage, engine hours, elevator hours, bin weights, lost and other downtime (servicing, breakdown, bin delays). This information was obtained from machinery gauges, meters of fuel tankers etc and recorded into logbooks. Subsequent analysis was undertaken.

Whilst, electronic measuring systems had previously been installed on machines (e.g. cane-loss monitor), Agnew (2002) was one of the first to implement logging capabilities, for collection of a range of machine data. Agnew (2002) fitted a number of harvesters with logging equipment to measure and record machine performance once during every minute of operation.

The data logging system collected fan speed, ground speed, basecutter pressure, chopper pressure, elevator on/off and top roller opening position. The system had an in-cab display of ground speed and top roller position. Operator feedback was enhanced with the inclusion of a forward speed display. A display of top roller opening position indicated machine pour rate and feeding characteristics. This was the first attempt at combining technology to comprehensively monitor machine performance.
The sugar industry has been using data loggers and GPS to keep records of the location of various vehicles for a number of years (e.g. trains, trucks). Mounting GPS on harvesters to monitor location and further development and application of machine performance monitoring has been adopted only more recently in work on harvesting pricing structures (Willcox et al. 2005) and integrating harvest and transport (Markley et al. 2003, 2006; Crossley and Dines 2003, 2004).

Mackay Sugar developed a harvester monitoring system to allow the machine status to be determined for harvester tracking purposes. In 2006, in four harvesters, the tracking system was expanded to include four analogue inputs. These included full engine monitoring, chopper pressure, feed roller pressure and primary extractor speed. This was undertaken to allow estimation of harvest yield (J Markley pers comm.).

Willcox et al. (2005) used purpose-built systems electronic harvester monitoring units incorporating GPS (accurate to ± 5 m), a data logger and a telephone modem. These systems monitored ground speed, engine status on/off, elevator status on/off, chopper status on/off and extractor fan speed. Fuel use was recorded manually and subsequently added to the data set. The ‘state’ of the harvester (e.g. stopped, cutting) was combined with block tonnes to calculate field efficiency, pour rates and delivery rates.

A limitation to the adoption of these systems has been the availability of a commercial ‘off-the-shelf’ system for harvesters. Previous systems were either adapted from systems in use in other industries (BIGmate-Industrial, MTData-Transport) or purpose built from individual commercial products (i.e. logger, sensors, GPS, modem etc). However, a number of commercial off-the-shelf systems are now available. These include a harvester tracking system marketed by BIGmate, Transom as used by NSW Sugar Milling Co-op, MTData system as used by Mackay Sugar and a harvester monitoring unit marketed by AgGuide.

The cost of these systems ranges from ranges from $2,200 exec GST for a basic AgGuide system up to $12,000 exec GST for a high level BIGmate system. Options for hire/lease are available for BIGmate.

TechAgro has developed an integrated automation package (Esquivel et al. (2007). They have developed a range of equipment specifically for sugarcane including georeferenced harvester data logging equipment, flow rate monitors, yield mapping, automatic base cutter height control and forward speed controllers linked to flow rate. The TechAgro system comprises an onboard computer with compact flash storage subsystem, sensors to record
engine state (on/off) and rpm, basecutter and chopper hydraulic pressure, primary extractor on/off and hydraulic pressure and feed train to monitor feed roller displacement, GPS positioning system and in-cab display. The automatic basecutter height control, harvester tracking and yield monitoring components of the system are in use in the Ingham district.

Their work is similar to harvest data reporting currently being trialled and developed by CSR, Mackay Sugar and the NSW Sugar Milling Co-op.

NSW mills have been investigating harvester tracking as a way of reducing time spent in keeping records of what paddocks were cut on a particular day, as well as implementing a practical, objective method of monitoring harvester performance with the view to implementing harvesting pricing structures to reflect quality of work and output, and for improved efficiency (Crossley and Dines 2004).

In the Burdekin, several harvesting groups are utilising technology to locate and track harvesters using GPS as part of a benchmarking system for harvesting businesses. This technology also allows collection of data such as elevator operation, primary extractor fan operation, fuel use and feed train chopper pressures.

Agtrix Pty Ltd is currently developing an expert system that will provide advice on operating within harvester best practice (HBP) guidelines (Figure 28). The system will read data from the sensors fitted on a harvester, interpret real time data using HBP logic to guide the operator, options to display data collected on a screen and collate data to give HBP index reports. For example this system may suggest ranges of reasonable fan speeds based on ground speed and yield estimate.

![Figure 28: Agtrix Pty Ltd Conceptual HBP Expert System](image)

Sugarcane H-E-L-P Services (2009) has developed a commercial real-time data logging system to monitor and measure harvest and haul efficiency – Sugarcane H-E-L-P Fuel Saver system (Photograph 14). The advantage of this system when compared to similar systems is that fuel consumption is continuously recorded using fuel flow meters. The
system comprises a datalogger with up to 32 analogue inputs, handheld PDA with Ethernet capability. Sensors wired to the computer record time and fuel data for the engine, chopper system, elevator state (on/off), turning on headlands, waiting in the paddock for another haul unit and warm-ups/downs. The hardware comprises of the wiring harness, fuel flow meters and in-cab display. Instantaneous fuel usage is displayed along with other machine state on the in-cab display. The data is downloaded to the PDA and then transferred to a PC where a dedicated software package enables analysis to be performed.

There are nine systems in use throughout the industry. The cost of the system is about $7000, with savings for multiple use applications.

This system allows the true cost of harvesting at a block level to be determined. Redtrail (2007) assessed their harvesting enterprise using this system. They reported that the system allowed performance comparisons between machines and areas, data on true efficiency and fuel saver enabled different types of payment systems reflect harvesting conditions to be considered. In addition, the data collected and analysis also enabled scenarios for changing the layout on their own farms to minimise the cost of harvesting.

PHOTOGRAPH 14: SUGARCANE H-E-L-P FUEL SAVER SYSTEM (SUGARCANE H-E-L-P SERVICES 2009)

All commercially available harvester performance systems can be configured to individual monitoring requirements. The driving force to implement this technology will be the production of harvester performance reports that can be used to track and monitor the efficiencies of harvesters for differential harvest pricing and to monitor key performance indicators for growers and contractors.

6.1.6 Crop-Handling Speed Control System

Work by Kroes (1997), Schembri and Garson (1996), Davis and Norris (2001), indicated that matching component speeds to ground speed would play a significant role in improving cane feeding performance and reducing basecutter damage. For a given ground speed, an overly high basecutter rpm will result in stool being cut by the blades multiple times. When the basecutter rotational speed is too slow for the forward speed, then a tearing cut results and stalks are torn off by the disc before a blade reaches the stalk; this causes severe damage to the stool.
Whiteing and Kingston (2008) developed a proof-of-concept prototype on-the-go speed-control system, designed to enable variable-speed control of the crop-handling components (gathering system and basecutters) during harvesting. This system ensures that the machine maintains a consistent feedrate and optimum performance by enabling manual automatic crop-handling component-speed variation with ground speed to compensate for variations in the crop.

The system provides electric-over-hydraulic control of each of the crop handling-component pump-drives supplying oil to forward-feeding components and basecutters allowing an in-cab programmable PLC to constantly adjust component speeds to match harvester forward speed. Where possible, off-the-shelf components were sourced and integrated into the system design.

The system revolves around a PLC interface (Photograph 15) that receives inputs from ground-speed radar and feed roller/basecutter speed sensors. The PLC is programmed to respond to different ground-speed inputs and then activate the two proportional electro-hydraulic flow controllers to increase or decrease oil flow to the harvester components, to constantly optimise component speed to ground speed.

**PHOTOGRAPH 15: PLC INTERFACE (LEFT) AND EATON ELECTRO-HYDRAULIC PV54 PUMP CONTROLLER (RIGHT) (WHITEING AND KINGSTON 2008)**

The operator can select three control modes, ‘manual’ (enters a percentage valve open, i.e. 50%), ‘set point’ (sets a target speed, i.e. 280 rpm and controls the speed using the feedback sensor), or ‘auto’ (which varies a target speed according to ground speed and feedback sensor). A proportional electronic pump-control unit available from Eaton Hydraulic was used and found to function effectively.

Field evaluation of the system found the system was very effective in responding to changes in harvester forward speed as the operator progressed from standstill through to full operating speeds along with handling sudden reductions in basecutter load from gaps within the row.

This concept introduces a completely new dimension of sophistication into the world of cane harvesting, bringing it into line with many other agricultural harvesters.
6.2 Benefits Delivered

Various harvester performance technologies have been researched and developed to provide machine performance feedback or automate machine operations to favour higher harvesting efficiency and higher sugar recovery.

Some of these concepts, such as the cane-loss monitor were developed to a commercial product and delivered significant benefits to the industry during that period in which they were available. These included providing ground speed measurement and a relative indicator of cane loss.

Whilst, the benefits to industry through reduced dirt and ground loss were quantified with automatic basecutter height control systems, most were only developed to a pre-production prototype stage and were never adopted by manufacturers.

The lack of adoption can be attributed to the technological nature (electronic) of these concepts and to some degree being ahead of their time, not being market ready and the additional cost to machines with these systems. The earliest development of a cane yield monitor is a good example of a key enabling technology developed for a system in which the industry was not prepared for. This early work nevertheless provided some useful information about yield monitoring in sugarcane.

Whilst these systems (with the exception of yield monitors) are not currently available to the industry, their importance in raising industry awareness of the issues associated with cane and sugar losses during their development is not diminished.

Significant benefits have been delivered to the industry through the development of harvester performance monitoring systems. These systems have benchmarked harvesting efficiency and have facilitated the adoption of Harvesting Best Practice. However, a limitation to the adoption of these systems has been the availability of commercial ‘off-the-shelf’ systems for harvesters.

Currently, there is no commercial system available to provide real-time feedback to the operator on machine settings and their impact on HBP.

6.3 Research Opportunities

- Machines still lack the performance quality feedback when compared to other harvesting equipment – both cane supply and infield job.

- Development of an adaptive on-the-go machine component control system.

- Further development of real-time systems for reporting of product quality should be a priority.

- Dirt in cane and basecutter damage are current industry issues. There is no reliable height control. It is suggested that research be conducted on the following two areas.
  - Evaluation of automatic basecutter height control systems – such as the pressure based Auto Tracker/TechAgro system.
- Development of a mechanical bascutter height control system similar to the Brazilian Floating bascutter suitable for the Australian Industry.

- Requirement for standardising harvester performance monitoring systems to include not only machine state but HBP feedback should be supported.
7 HARVEST AND TRANSPORT INTEGRATION

7.1 Harvest Monitoring

The sugar industry has been using GPS as a management tool to keep records of the location of various vehicles for a number of years. The first commercial GPS vehicle tracking system developed in Australia was the GEOSTAT locomotive tracking system developed by Tully Sugar Limited and GS Corporation in 1993 (Fuelling and Wright 1997).

Knowing how much cane remains to be harvested during a crushing season has always been an important task undertaken by mill field staff. The pre-season crop estimates form the basis of many facets of raw sugar manufacturing from marketing and logistics, planning mill start dates, cane transport arrangements, harvest groups base daily loadings and harvesting schedules. Changes in farm estimates during the season often occur and will therefore affect many of those facets identified above.

Traditionally, mills used a proportional re-estimating program to determine the amount of change in farm estimates. In its simplest form, this is the calculation of a ratio comparing the actual yield for an area of harvested cane against the original estimate for that same area and applying the calculated ratio to the remaining crop estimates for each farm.

Developments in harvest management systems have seen the mounting of GPS on harvesters to monitor where harvesters have worked. Various harvester monitoring systems are currently in use with the main components comprising data logger, GPS and modem (See section 6.1.5).

Mackay Sugar in 2001 trialed a GPS harvest monitoring system which incorporated the BIGmate monitoring system located in the harvester. A GPS tracking device recorded the position of the harvester at 30 second intervals and stored it in a data logger awaiting download to the BIGmate web site and from there to Mackay Sugar (Markley et al. 2003).

Mackay Sugar continued development of their harvester monitoring system and extended their program to 42 harvesting groups during the 2005 and 2006 seasons. MTData tracking and data logging units are now the basis for the harvester performance and tracking system. They include elevator on/off and engine on/off digital inputs to allow the status of the machine to be determined. MTData units were selected over BIGmate units due to the flexibility and availability in purchasing the technology outright versus lease arrangements (J Markley 2008 pers comm.).

Crossley and Dines (2004) undertook trials to integrate harvester tracking with a mill-based spatial harvest recording system during the 2002 and 2003 seasons in the NSW mills. In this work, the hardware was a dedicated system assembled by Transcom, and consisted of an MPG data logger, Garmin GPS and a CDMA modem. The data recorded by these units consisted of a series of positions of the harvester, with the status of the sensors at those times. The NSW fleet was configured to monitor the engine, feed rollers/ choppers, elevator and base cutters. The sensors were digital, meaning that they could record only two states (on/off). A data point was recorded whenever either one of these sensors changed its status (on/off), or at 30 second intervals (Crossley and Dines 2004).
Harvesters monitoring data was stored on the harvester for the day and uploaded to a central server each night. The data was interpreted to generate GIS data representing the tracks of each harvester using a program named FRANK (named after a cane officer at Mulgrave Mill). Each segment of these tracks was interpreted for what the harvester was doing at the time from the state of the sensors, as well as speed that the harvester was traveling, the paddock it was working in and whether it was cutting or not. GIS data showing the harvester tracks and areas cut were stored in spatial database. A customised GIS software application called CHOMP (Centralised Harvest Operations Management Program) was used to interpret the areas cut and maintain the paddock harvest status from a map interface (Beattie and Crossley 2006).

![Figure 29: GPS Harvester Tracks in a Harvested Field, Coloured by Speed (Beattie and Crossley 2006)](image)

Emerging technologies are currently being implemented to enhance operations through an integrated approach to establishing communication links from the relevant databases to harvesters and locomotives automatically. Mackay Sugar has established communications to harvesters and locomotives through the introduction of an MTData mobile tracking package that consists of a GPS tracking unit and a VGA touch screen data terminal communicating to the mill via the Next G network (Markley et al. 2006).

At Mackay Sugar, the combination of electronic cane bin consignment, accurate GPS location of bin harvest position and NIR scanning technology at the mill has allowed the reporting of the actual quality of product (delivered through NIR scanning technology at the bin level) to the location within the paddock that the cane was harvested from (Fleming et al. 2006).

Fleming et al. (2006) developed a new cane payment scheme based on NIR analysis and implemented across Mackay Sugar for the 2005 season. The system is based on value chain principles of sharing risks and rewards, and removing obstacles to cooperation between the sectors.
A prototype electronic consignment system was developed using a touch screen interface and mobile data communications to transmit delivery details direct from harvesters to the mill. Whilst the system showed promise in trials further refinement is required before it can be widely deployed (Fleming et al. 2006).

Harvester position, operating data and time data from harvester tracking and data units is relayed across the mobile data network to the central database and processed by the CHOMP software package to produce thematic maps and reports of speed, area harvested, field efficiency etc. NIR analysis of cane quality data including dirt and extraneous matter and on-line reporting via the web portal was also trialled, with the ultimate objective of drafting new harvesting contracts between the milling, growing and harvesting entities based on market signals, cane quality and best practice incentives.

This spatial measurement of cane quality will potentially allow growers to be able to determine where productivity gains can be achieved through modification of on-farm practices and importantly facilitate the adoption of harvest vest practice.

An integrated harvester performance and monitoring management system offers the sugar industry significant improvements over existing harvest and transport operations. Technologies have already been implemented in a number of mill areas such as Mackay Sugar and NSW Sugar Milling Co-operative to enhance operations and add value to harvest and transport management.

### 7.1.1 Benefits Delivered

The demonstrated benefit to the Australian sugar industry has been through the development of an integrated spatial harvest management system and subsequent implementation in a number of mill regions. This has been achieved through:

- The development of automatic harvest progress recording systems using machine sensors, GPS and digital communication should be supported.
- The development of a dedicated program to interpret harvest progress data and to generate GIS data (FRANK).
- The development of a customised GIS software application called CHOMP to interpret the areas harvested and maintain the paddock harvest status from a map interface.

### 7.1.2 Research Opportunities

- Development of a commercial automatic harvest progress recording system using machine sensors, GPS and digital communication.
7.2 Value Chain Analysis

Value chain research in the Australian sugar industry has evolved considerably in the past decade - one of the efforts in the industry aimed at getting better. Value chain research has been very complex and expensive due to the scientific and technical modelling involved.

Higgins et al. (2005, 2006) outlines the evolution of value chain research and shows that there has been a strong focus on the harvest and transport sectors. Harvesting and transport have attracted a large amount of R&D as it provides more logistical challenges than do the other sectors upstream of the mill. Many opportunities in these sectors (such as harvester/siding rosters, time window of harvesting, just-in-time scheduling) have economic benefits that are easy to quantify, and some can be addressed with some of the more traditional supply chain methodologies (Higgins et al. 2006).

The first value chain project that identified and addressed opportunities across the harvesting/transport interface of the chain showed potential cost reductions of $2 and $3 per tonne of cane (Grimley and Horton 1997, Grimley et al. 2001). The models were developed for the Mossman, Mulgrave and Tully sugar regions, through consultation by Price Waterhouse Coopers (formerly the Operations Research consultancy group).

Higgins et al. (2004), showed potential economic benefits between about $1.00 and $2.50 per tonne of cane, as well as up to a 95% reduction in bin delivery delays, depending upon the level of operational, tactical and strategic change.

Further studies over the past five years, there has been a rapid increase in the adoption of improved logistics at the harvesting-transport interface, particularly for siding rosters or increased time window of harvesting (Mackay, Mossman, Mourilyan, Maryborough) (Higgins et al. 2006).

Higgins et al (2006) reported that in the Herbert, an average reduction in harvesting costs of $0.27/ct (or a predicted $1 350 000 per year given a 2005 size crop) can be realised from reduced waiting time for bins and larger sidings. They also suggest that there is also the potential for significant savings in transport costs in this region from an estimated 60% reduction in shunting times and spreading the demands on locomotives across the 24 hour day.

Prestwidge et al. (2006) investigated the opportunities for adding cane loading pads for road transport to reduce haul-out distance and consequently the costs of harvesting across three mills regions in NSW. They adapted two existing modelling tools to the NSW sugar region, namely the Siding Optimisation Model (Higgins and Laredo 2006) and the Harvest Haul Model (Sandell and Prestwidge 2004). The Siding Optimisation Model, originally used for locating sidings on a cane railway system, was adapted to the road transport system in NSW and was named the Pad Optimisation Model. They suggested harvesting cost savings of $786 000 over 5 years (across the three mills) could be realised from investing in additional loading pads at optimal locations. The outcome of this study was the expansion of existing pads and the construction of new pads to reduce haul distance. This is an essential component of the whole-of-crop harvesting system adopted by NSW Sugar Milling Co-op (NSWSMC).
Beattie and Crossley (2006) investigated a number of new techniques for harvest and cane supply management. They implemented an automated harvest management system called CHOMP (Crossley and Dines 2004) and examined more efficient harvest arrangements through the use of modeling tools (Higgins et al. 2006).

Agtrix Pty Ltd and the NSWSMC pioneered the development of CHOMP that is now used widely in the Australian sugar industry. The NSWSMC now has a fully operational automated harvest management system that is used to receive and interpret data from harvesters on daily operations and process this information to maintain harvest records on how much cane is cut and to develop harvester performance reports. Implementation of this automated system has reduced the cost of cane supply operations at the NSWSMC by 32% (Beattie and Crossley 2006).

Beattie and Crossley (2006) evaluated scenarios for harvesting group optimisation and the formation of one harvesting co-operative per mill area. They found that there are savings of between $0.50 to $1.00 per tonne to be gained by the NSWSMC if amalgamation of harvesting groups either as a one single group or two-group scenario occurred.

Higgins et al. (2006) reported that there is limited published material highlighting non-logistical value chain work such as increasing information transparency, building new markets, or business process integration in the Australian sugar industry.


From a modelling and computational perspective, it is difficult to capture decision making between the farming and milling sectors (inclusive), while considering scales of interactions at a paddock and a mill level simultaneously. Thorburn et al. (2006) used a multi-agent approach, which aimed to link up existing sugar industry models representing each of the sectors.

Fleming et al. (2006) developed value chain management strategies for the Mackay region underpinned by technology. The technological component consisted of a web portal, shared regional database and software tools that link the members of the value chain and facilitate the sharing of information for mutual benefit. This led to the implementation of a new cane payment formula in the 2005 harvest season, which better promotes growing region-wide revenue and dividing revenue more equitably.

7.2.1 Benefits Delivered

This program of research has delivered demonstrated benefits to the Australian sugar industry. These include:

- A greater common understanding across the industry sectors to the impacts of a wide range of value chain opportunities in the combined harvesting and transport sectors. The potential economic benefits have been estimated to be between about $1.00 and $2.50 per tonne of cane.

- Improved collective planning across the growing, harvesting and milling sectors to win-win solutions that also maximise industry profitability.
• Improved logistics at the harvesting-transport interface, particularly for siding rosters or increased time window of harvesting (Mackay, Mossman, Mourilyan, Mulgrave, Maryborough). For example adoption of increased time window of harvest (from about 12 hours to 18 hours per day) in Mourilyan from 2003 onwards, by 2006, the Mossman region was heading towards a 20 hour time window of harvest and in 2008 the time window of harvest was extended to 6pm in the Herbert region. This has led to reductions in waiting time for bins and improved utilisation of the each mill’s bin fleet.

• An enhanced understanding of the benefits of alternative cane supply arrangements to growers, harvesters and the overall industry.

• About 75% of the industry has explored the possibilities of using optimised harvest scheduling in their region, resulting from the application of SugarMax and delivery of schedules to their regions. Adoption of optimised harvester rosters in both mills of the Herbert region during the 2005 harvest season. Harvester rosters were developed to improve daily balances of cane supply to each of the mills and along the branch lines.

• Rationalisation/upgrading of transport networks. For example the expansion of existing pads and the construction of new pads to reduce haul distance in NSW, siding upgrades/rationalisation in the Herbert region.

• Adoption of the Harvest Haul Model to evaluate various options for reducing costs at the harvesting-transport interface. The demand for the Harvest Haul Model has increased rapidly across the sugar industry and is expected to continue as it is further developed and integrated with harvester tracking (CHOMP). The Harvest Haul Model will be used for across 70% of the industry to investigate various options, including harvesting group amalgamation, dual row harvesting, improving efficiency of harvesting businesses and changes to the transport system.

The quantitative benefits of value chain research such as reduced harvesting costs and reduced sugar losses have been made difficult by the lack of quality data and due to the rapid changes in harvesting and transport systems (e.g. major fluctuations in cane yield and harvester numbers).

Whilst, there is no doubt that system research has delivered benefits to the industry, factual data is imperative to quantify benefits with respect to harvester performance. There is also strong interest from sugar industries in Brazil, USA, India and Thailand on the concept of using mathematical models to optimise harvest schedules to exploit geographical differences in sugar yield. Whilst this may represent some leakage of this technology to overseas industries it also is a surrogate indication that benefits are being delivered.

7.2.2 Research Opportunities

• Development of a quantitative evaluation methodology that is effective for value chain research. Uncertainty in the system and a moving baseline will need to be accommodated. Harvesting and transport system can change rapidly with fluctuations in cane yield, harvester numbers and implementation of new farming systems.
• Value chain models are well developed and from a modelling perspective, there should be minimal further research required at the harvesting transport interface. Some work will be needed to adapt the tools to different regions, though this process should be quite minimal.
8 The State of Play in the International Sugar Industry

In many developing countries, the future of sugarcane harvesting and other aspects of cane production undoubtedly lie in increased mechanisation. These industries are experiencing increasing difficulties in finding labour for hand harvesting. Therefore, the proportion of the world’s crop harvested by machine will increase. However, like Australia, mechanisation may have negative effects on productivity. In South Africa, an industry undertaking conversion from hand harvesting to mechanised harvesting, Meyer and Van Antwerpen (2001) proposed that the increased mechanisation in the sugar industry is largely responsible for the reduced number of viable ratoon crops.

Brazil, Florida, Louisiana, Columbia and Argentina have all developed strategies to assist in the move to ‘chopped cane’ harvesting. The diversity being much greater than is seen in the Australian industry, and again reflects the way mechanisation has been adapted to suit different conditions.

There are very strong common threads in the issues all these countries are experiencing with the performance of the current harvester designs.

8.1 Brazil

In 2008, in the Centre-South (CS) region of Brazil 500 million tonnes of cane with an average yield of 87 t/ha was harvested. Of this about 53% was mechanically harvested. In the North East, 60 million tons with an average yield of 70 t/ha was harvested. Of this 10% was mechanically harvested (JLM Neves 2009 pers comm.).

Given the size of the Brazilian industry as a whole, its various sugar estates and its move into ‘chopped cane’ harvesting, it is no surprise that the Brazilians have been active in exploring the issues of machine performance.

Case IH dominating the market with 60% of machines, 35% Cameco/John Deere and 5% Santal harvesters. The Brazilian market now approaches 1000 machines per year. There will be about 9 machines sold into Australia in 2009.

Whilst the move to green cane harvesting was primarily made on public health and environmental grounds (Kyoto agreement on greenhouse gas reductions), the adoption of green cane harvesting will further enhance both the environmental position of the Brazilian sugar industry and further reduce production costs.

The move to green cane ‘chopped cane’ harvesting, and the reorganisation of the harvest and transport system that this has dictated, means that 'burn-to-crush' delays of 3 - 4 days have been reduced to 'cut-to-crush' delays of hours. This has had a positive impact on Brazilian sugar quality.

The use of ethanol as a sink for poor quality sugarcane, and allowing increased season length by the use of early and late season cane, allow cost-effective production of high quality sugar. Figure 30 illustrates the projected sugar versus ethanol for the Centre-South region of Brazil.
High utilisation of capital throughout the industry is obvious. The integration of ethanol with co-generation and sugar production allows extended season length, giving enhanced capital utilisation for harvesting equipment, transport equipment and milling facilities. It also extends the period of demand for labour.

The general use of 24-hour harvesting and the use of ‘fronts’ of harvesters dramatically impact on harvester utilisation. Harvester and associated transport systems operate on a 'just in time' basis. The highest priority is to keep the mill operating, but with the minimum number of harvesters, infield haulouts and trucks.

In general, harvesters are operated at low pour rates to maximise product quality. The product quality coming from most harvesters, particularly in the more humid areas, is extremely high because of this. Norris (2001) noted that all harvesters, however, are not necessarily operated in this mode, for example, at Da Barra.

The use of dataloggers on the harvesters (Sao Marthine Mill); accurate record keeping to maximise harvesting equipment productivity (De Pedra Mill); and GPS fleet management systems (several mills) to optimise the performance of the transport systems demonstrates that countries such as Brazil can 'lead the world' in the adoption of 'Worlds Best Practice'.

There is significant concern as to the effects of soil compaction on long-term productivity as the industry moves to single row harvesting. The industry has adopted the use of low-pressure tyres and maintains axle loads below 7 tonnes.

In 2004, Case IH the parent company of Austoft Industries closed their Bundaberg factory and moved operations to their Piraciaba plant in Brazil. Hence, research and development is primarily undertaken in Brazil. John Deere has a manufacturing factory in Goias state of Brazil, just for building for Brazil demand.
The move into aluminium bins on the road transports allows maximisation of payload on the public roads. Again, this and the use of low tare weight field haulouts help maximise harvesting efficiency and minimise costs. NSW Sugar Milling Co-op has recently moved to aluminium bins for road transport as an integral component of their whole-of-crop harvesting system (Lamb 2008).

Quality research in now being conducted in Brazil on both harvester performance and the impact of harvesting on productivity. Research by the CTC – Technology Center Canavieiras the technology arm of Copersucar has led the way. The Brazilians are well aware of most research being undertaken in Australia.

Neves and Perticarrari (1998) and Neves (2003) undertook a program to investigate losses associated with chopper harvesting. They studied invisible losses, defined as the juice and unidentifiable fine juice-holding particles discarded by the harvester as opposed to the visible losses which are identifiable, and the primary extractor’s cleaning efficiency.

They undertook trials under controlled conditions using a stationary harvester which was fed material by a conveyor. For invisible loss trials, clean cane without leaves, straw and tops were processed and the closure of the material balance was termed the invisible loss.

They reported invisible losses for the basecutter of 0.79%, feed train, choppers, extractor and elevator was 2.4% (fan speed of 1350 rpm) and 1.4% for a fan speed of 1000 rpm. The total invisible loss was 2.2 – 3.2%.

In Brazil, in 2006/2007 season 53% of the total chopper harvested area is on 1.5 m row spacing and 38% on 1.4 m.

Neves (2003) developed a novel system for controlling basecutter height in an attempt to improve the performance of basecutters. This system called the ‘floating basecutter’ differs to all previous attempts to control basecutter height by suspending the base cutter gearbox and associated components as a discrete module which can move independently of the harvester mainframe. Neves et al. (2003) reported on performance evaluation of the floating basecutter.

The floating basecutter is an example of technology developed in Brazil that could have significant benefits to the Australian industry.

Precision agriculture is also being applied in Brazil. Pagnao and Magalhaes (2001) and Cerri and Magalhaes (2003) report on the development and testing of yield monitoring technology.
8.2 Columbia

The Columbian government had anticipated a cessation of burning cane prior to harvest by 2005. Whilst, there are strong incentives from the government against pre-harvest burning, a percentage of the Columbian crop is still harvested burnt. The primary reason for this is the size of crops, which require burning due to the inadequate feeding performance of current machines.

Larrahondo and Briceno (2001) at the Columbia Sugarcane Research Centre (CENICANA) investigated sucrose losses in processes prior to mill operations.

They reported that sugar yield reduces by 0.14 to 0.23% for each one percent increase in trash and those losses associated with harvesting and transport processes are between 0.5 and 1.5 Pol% cane. No details of the methodology are given.

8.3 Florida

The Florida sugarcane industry can be argued to most closely represent the Australian industry. The industry can also be argued to epitomise the worst aspects of machine harvesting of sugarcane (Norris 2001). The use of 1.5 m crop row with 1.8 m equipment spacing is similar to the majority of the Australian industry. However, unlike in Australia soil compaction is not seen as an issue.

Norris (2001) reported that the cane payment system at Bellegrade Mill discounts the total weight of cane by the percentage 'material other than cane' in one hand-sorted sample per harvesting front per day. In addition, they noted that the 'low-boy' harvester transporters are an innovative design, which would appear to offer significant advantage to the Australian industry.

Harvesting large unburnt crops is looming as a major issue for the industry, and current harvester designs are seen to be clearly inadequate, primarily from the ability to gather the cane effectively and from stool damage and removal during harvest.

Despite the rhetoric, green cane harvesting will be introduced, further increasing the pressure on manufacturers to improve the performance of harvesters.

8.4 Louisiana

The Louisiana industry can be argued to be the North American industry with the most to offer the Australian industry, particularly the Australian 'wet belt' industries in north Queensland and northern NSW. In these environments, the system of 1.83 m rows and controlled traffic appears to offer very significant potential including:

- The controlled traffic system gives mobility and ability to maintain harvesting under extremely adverse harvesting conditions.
• The raised bed into which the cane is planted allows the cane to grow without fear of waterlogging, even when free water is present in the traffic furrows.

• Harvesting under wet conditions does not adversely impact on the potential of the ratoon crop, because there is little potential to damage the raised bed area where the cane is growing.

Norris (2001) reported on the LA Cane ‘Tiger’ harvester, which incorporates a number of alternative concepts. He noted the reduced weight of the machine and the concept of pre-stripping the cane before billeting. Whilst the ‘Tiger’ embodies a range of interesting concepts, the company has since dissolved along with the ‘Tiger’ machine.

Romaro et al. (1996) and Richard et al. (1996, 2001) have focused on comparison between wholesstalk harvesting and chopper harvesting. Romero et al. (1996) reported that increases in theoretical recoverable sugar (TRS) from improved varieties have not been accompanied by improved harvesting practices.

Milligan et al. (1994) and Richard et al. (2001) reported that EM removal is difficult during harvesting of LCP 85-384 the major variety planted on 90% of the Louisiana acreage. This is due to its small stalk diameter and tight leaf sheath.

Further research by Viator et al. (2007) has been conducted on the combined effect of selected ground and fan speeds on sugar yield, cane quality, and field losses in LCP 85-384 during chopper harvesting. They benchmarked the performance of a John Deere CH3500 at ground speeds of 4.0, 4.8, and 5.6 km/hr (indicative of pour rates of 67, 80, and 91 t/ha) under local green cane harvesting conditions with primary extractor fan speeds of 650, 850, and 1050 rpm.

When harvesting LCP 85-384 under optimal conditions, the 1050 rpm fan speed increased TRS by 10% but decreased cane yield by 15% compared to the two lower fan speeds resulting in similar sugar yields for all fan settings. Under poor conditions, the 1050 rpm setting decreased cane yield by 13%, without an increase in TRS, resulting in lower sugar yields than the low and medium fan settings. This research supports the work by (Whiteing et al. 2001) where harvesters perform well under ideal conditions, but cleaning performance and cane quality decreases sharply under poor conditions regardless of fan speed.

Despite the high levels of subsidy required to make it viable, the Louisiana industry is rapidly embracing the new technology of chopper harvesting. In this context, they have modified farming systems to suit chopper harvesting to match with their controlled traffic system, however are faced with similar issues to the Australian harvesting sector.
8.5 Argentina


The research agronomy team at Ledesma has a long history of harvest research. Past projects have included modification of base cutter design, assessing the impact of base cutter speed, pressure and height on cane loss and ratoon performance and development of better cane cleaning systems. A basecutter design was adopted for the new Cameco 3510 harvester (models with the Ledesma basecutter design are not available in Australia) (McDonald et al. 2005).

At Ledesma a move from burnt cane harvesting to green cane harvesting is being implemented. There are a number of agronomic reasons (e.g. moisture retention, weed control, soil health) for the transition but one of the most important was the community pressure to stop burning. Currently about 60% of the region is harvested green. A key component of the transition is the adoption of harvesting best practice guidelines developed by Australian researchers such as Agnew 2002, Whiteing et al. (2001) and Whiteing et al. (2002).

Gomez et al. (2003a, 2003b) reported on the results of a comprehensive testing program to assess cane and juice losses during mechanical harvesting. They used the mass balance methods to assess the quantity of cane and sugar losses at each process stage between harvesting and shredding at the mill. In a series of 31 trials using CH2500 chopper harvesters, sucrose losses averaged 18% of that available before harvest in green cane and averaged 16.5% sucrose losses in burnt cane.

Gomes et al. (2003) reported that ratooning is much improved when following best harvesting practice guidelines. Most importantly, they report increased returns in the order of $A3 per tonne of cane when implementing best harvesting practice. This is a greater potential benefit than Australian researchers estimated, and shows that the Australian industry can benefit from the experience of overseas industries in implementing new technologies.

Gomes et al. (2006) reported losses due to burning, billeting and in the trash of 12.4% in green cane and 15.7% in burnt cane. Primary extractor losses of 3.4% were reported in green cane versus 0.3% in burnt cane conditions. Therefore actual losses and realised tonnes of sugar per ha were similar between burnt and green cane.

They found irretrievable loss of sugar from burning. There were similar losses of sugar from green cane harvesting but these were considered to be largely retrievable through improvement in harvesting practice. The results show that, while CCS losses from burning were large, they were in part compensated for by the higher impact of trash on CCS in the green cane and higher in-field losses from harvesting green. The results also demonstrate the significant losses of sugar caused by the act of chopping whole-stalks into billets.

Ledesma’s adoption of harvesting best practices has demonstrably reduced green cane losses. Their aim is to deliver the best quality biomass to the mill. This involved topping where possible and separating trash and cane in a cane cleaning plant at the mill. However,
in order to realise the full benefits of green cane harvesting, infield losses still need to be addressed (Gomes et al. 2006).

Scandaliaris et al. (2004) reported cane losses of 3.6% to 5.8% with a new model harvester compared to 4.8% to 7.7% with the older model harvester at a 1000 rpm fan setting.

### 8.6 Benefits Delivered

International industries are following early Australian harvesting research. Those industries moving into ‘chopped cane’ harvesting mainly as a consequence of labour shortages are embarking on programs aimed at comparing ‘chopped cane’ wholestalk harvesting in burnt cane. Those industries which are moving to green cane harvesting are embarking on programs aimed at comparing machine performance in green and burnt cane. International industries are acutely aware of Australian harvesting research.

SRDC has continued to invest in travel and learning opportunity projects for overseas research and extension. Such investment has achieved great levels of success for both groups and individuals.

The Australian sugar industry has gained a number of benefits from these international experiences. These include:

- Brazilian operations have demonstrated that larger scale sugarcane operations can produce world’s best practice sugarcane agriculture. Undoubtedly Australian operations have opportunities to gain efficiencies by improving our scale of operations.

- Quantified the magnitude of in-field losses associated with ‘chopped cane’ harvesting in both green and burnt cane. This has confirmed the results of Australian research.

- Quantified the magnitude of cane and sugar losses at each process stage between harvesting and shredding at the mill losses. This has supported Australian research and is a key requirement to progress cane harvester development.

- Developed novel solutions to reduce cane and sugar losses which can be readily implemented in the Australian Industry – e.g. floating basecutter.

- Implemented harvesting best practices for whole-of-system gain and demonstrated reduced field losses of cane and juice during chopper harvesting. This shows that the Australian industry can benefit from the experience of overseas industries in implementing new ‘ready to apply’ practices.

- The Australian and International harvesting sectors are faced with similar issues such as feeding heavy lodged crops, reducing infield losses, whole-of-crop harvesting (termed integrated harvesting in Brazil). Progress in cane harvester development will become increasingly challenging and will depend on the reliability of machine performance testing.
9 CONCLUSIONS AND RECOMMENDATIONS

The following recommendations reflect the general thrust of the review. Further ideas and specific actions are indicated in the text of the report to stimulate debate on practices and direction of harvesting research funded by industry.

Manufacturer’s perceive the worldwide market for cane harvesters to be small, relative to the market for ‘mainstream products’. The Australian cane harvester market is very small in comparison with other countries such as Brazil. Hence, it is unlikely that large sums will be invested in new technology and in particular for Australian requirements. Therefore it is imperative for continued machine improvement that there is a program of industry support aimed at reducing infield losses.

1. There are two major issues facing the Australian sugar industry that may lead to significant changes in harvester design and harvesting systems. These are new farming systems and the cost of harvesting. The industry must have a clear vision of the purpose of the machine and design considerations to allow targeted investment. The key tasks in RDE for these issues are as follows:

a) Industry must move towards a controlled traffic system and therefore there is a requirement to develop harvesting strategies and solutions for row spacing configurations.

b) Assessment of the utility for wide-swath harvesting to contain harvesting costs, the most appropriate machine design and impact on the value chain. The Industry needs to identify opportunities to achieve wider-swath harvesting under a controlled-traffic system i.e. limitations with Corradini Two-in-One® type systems.

c) Evaluation of the issues with current machines associated with increased pour rates.

2. A fundamental understanding of the machine-crop interactions in particular the principles and concepts associated with gathering, feeding, basecutting, billeting and cleaning of sugarcane has been gained through component research. This has raised awareness of the issues involved during these processes and been the catalyst for novel industry-led approaches to improve the performance of machines. It has also led to world-leading technological innovation in mechanical harvesting from which the industry has directly benefited, which would not have occurred without the assistance of industry research.

Opportunities for industry research on machine components will need to be prioritised and based on machine purpose and design considerations. For example green versus whole-of-crop, wide-swath machine etc. Based on the foregoing discussion, the key tasks required in RDE on machine components are:

a) In harvesting systems where the differentiation and removal of tops and green leaf is required an improved topping system will be required (dry leaf with cane, green leaf rejected).

b) The current crop divider linkage system tends to be dynamically unstable. An industry-led, simple, cost-effective solution (dynamically stable) for controlling the height of the crop-dividers should be encouraged.
c) Evaluation of the impact of volumetric capacity and feeding efficiency when harvesting for high biomass systems (whole-of-crop, high pour rate).

d) Initiation of a program for assessment of alternative concepts for cutting and billeting of sugarcane within the context of minimising percentage loss per cut per metre.

e) The impact of current industry pour rates on feed train/chopper system configurations and cleaning systems with a particular emphasis on resulting damage and sucrose losses is a priority.

f) In harvesting systems (e.g. whole-of-crop harvesting and/or wide-swath harvesting) where delivery capacity of elevators is a limitation then alternative developments should be assessed.

3. Industry research has demonstrated that there is potential to increase industry profitability without capital investment through reduction in field losses of cane and juice during harvesting. This outcome has been demonstrated and confirmed in overseas industries. Adoption of HBP has been slow due to industry skepticism about sugar loss levels and pressure to minimise extraneous matter and transport costs. The invisible nature of the sugar loss makes it difficult to convince some industry stakeholders of the importance of HBP. HBP should be a priority for the industry as the benefits have been defined.

Based on the foregoing discussion, key tasks are required in RDE to facilitate adoption of HBP practices. These are as follows:

a) Standardised method of testing – mass balance v direct methods.

b) Assessment of sucrose loss from machine process modifications in retro-fit developments and embodied in late model machines e.g. Anti-vortex, 12 blade chopper systems.

c) However, educating the industry of the drivers of HBP and that there is no prescriptive setting to minimise EM and cane loss.

d) The benefits achievable from HBP operation and the costs incurred by harvester operators need to be clearly defined, and a payment system which rewards operators for adopting HBP thus enabling the industry to realise the financial benefits.

e) Real-time and accurate feedback is required to overcome the existing harvester-payment system and enable negotiation of the best possible job at an acceptable price for individual blocks.

f) Progress in harvester development depends on the reliability of performance testing. This includes cane and sucrose loss measurement, not only in test facilities, but also in the field. A method to quickly and accurately measure cane loss directly from field residue samples would be a massive boost to the promotion and adoption of HBP to minimise sugar losses.

4. Various harvester performance technologies have been researched and developed to provide machine performance feedback or automate machine operations to favour higher harvesting efficiency and higher sugar recovery. Machines still lack the performance quality feedback when compared to other harvesting equipment – both cane supply and infield job.
Key tasks are required in RDE to allow implementation of HBP practices, harvest and transport integration and provide quantifiable data for value chain analysis. These are as follows:

a) Development of an adaptive on-the-go machine component control system.

b) Further development of real-time systems for reporting of product quality and standardising performance monitoring systems to include not only machine state but HBP feedback inclusion. Any feedback system requires accurate, real-time feedback on incoming cane quality, i.e. NIR.

c) Dirt in cane and basecutter damage are current industry issues. There is no reliable height control. Evaluation of automatic basecutter height control systems – such as the pressure based Auto Tracker/TechAgro and development of a mechanical basecutter height control system similar to the Brazilian Floating basecutter suitable for the Australian Industry should be considered.

5. Over the last few years there has been a ground swell to move towards a more inclusive model of R&D industry research. This value chain approach has evolved considerably and is an example of the industry’s efforts at getting better. Whilst, there is no doubt that this research has delivered benefits to the industry through improved collective planning, logistics and enhanced understanding of the benefits of alternative cane supply arrangements, factual data is imperative to quantify benefits with respect to harvester performance.

Value chain models are well developed and from a modelling perspective, there should be minimal “foreseen” further research required at the harvesting transport interface. Some work will be needed to adapt the tools to different regions, though this process should be quite minimal.

The quantitative benefits of value chain research such as reduced harvesting costs and reduced sugar losses have been made difficult by the lack of quality data and due to the rapid changes in harvesting and transport systems (e.g. major fluctuations in cane yield and harvester numbers). Therefore a key task RDE is as follows:

a) Development of a quantitative evaluation methodology that is effective for value chain research. Uncertainty in the system and a moving baseline will need to be accommodated. Harvesting and transport system can change rapidly with fluctuations in cane yield, harvester numbers and implementation of new farming systems.

Simultaneous to all these activities will be the need to keep abreast of overseas developments in harvester components and performance. Support for grower, consultant and researcher visits to technical meetings, centres of expertise and manufacturers to assess new, ‘ready-to-apply’ developments would therefore be highly valuable.
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