SIMULATION MODELLING OF SUGARCANE HARVEST-TO-CRUSH DELAYS

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ABSTRACT

Long delays between harvesting and crushing of sugarcane lead to excessive deterioration in the quality of sugarcane. The aim of this project was to develop a computer based model of sugarcane harvesting and delivery systems that could be used to investigate methods of reducing harvest-to-crush delays. A literature review was conducted and simulation modelling was chosen as the most appropriate modelling technique for the situation of sugarcane harvesting and delivery and the purposes of this project. The Arena modelling system was chosen as the simulation software with which to construct the model.

A model was developed on the scale of a particular sugar mill and the area of farms supplying it with cane. The Sezela mill on the south coast of KwaZulu-Natal, South Africa was chosen as a case study on which to develop and test the model. The model integrated a harvesting and transport section which represented all the individual farms or combinations of farms in the area with a millyard section.

After the model had been verified and validated, it was used to investigate the effect of a number of different scenarios of harvesting and delivery systems and schedules on harvest-to-crush delays in the Sezela mill area. The results of the experimental runs performed with the model indicated that the most significant decreases in harvest-to-crush delays could be brought about by matching harvesting, delivery and milling cycles as closely as possible. It was also evident that burn-to-cut delays where daily burning is not practised constitute a large proportion of overall harvest-to-crush delays. The model proved to be useful in making comparisons between systems and in providing a holistic view of the problem of harvest-to-crush delays. Recommendations for future developments of the model include adding a mechanical harvesting component and making the model more easily applicable to other mill areas.

I wish to certify that the work reported in this dissertation is my own unaided work except where specific acknowledgement is made. In addition I wish to declare that this dissertation has not been submitted for a degree in any other university.

Signed: ....

A.J. BARNES

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1. INTRODUCTION

When sugarcane is burnt or cut, the quality of the cane starts to deteriorate and this process of deterioration continues until the cane is crushed in the milling process. The deterioration in the quality of sugarcane involves the loss of sucrose content and the formation of other products such as ethanol, dextran and oligosaccharides. This leads directly to monetary losses to the grower since he/she is paid on the basis of the sucrose content of the cane that he/she delivers to the mill, as well as to the millers, since the other products formed in the deterioration process interfere with the milling of the cane, causing exhaustion and crystallisation problems (Morel du Boil, 1995). Exhaustion refers to the amount of sucrose remaining in the molasses, which is a byproduct of the milling process and crystallisation refers to the quality of the sugar crystals that are formed. In the South African sugar industry, the issue of cane quality is set to become more important with the proposed introduction of a new system of cane payment which will reward growers for the quality as well as the sucrose content of the cane which they deliver (Brokensha, 1997).

The amount of deterioration that occurs in sugarcane after harvesting is dependent on numerous factors, including whether or not the cane was burnt before cutting, the cane variety and the weather conditions and condition of the cane at harvest (Egan, 1968; Wood and Du Toit, 1972; Lionnet, 1986; Sharma, 1994). However, most of these factors are not always within the control of the miller or the grower and it is over time that the deterioration occurs and therefore, limiting the time between the harvesting and crushing of the cane is likely to have the most significant effect on the amount of deterioration that can occur. An investigation into harvest-to-crush delays was conducted by the Sugar Industry Central Board (SICB) in 1975 (Brokensha *et al.*, 1975) with the stated objectives of discerning the causes of delays and seeking practical methods of reducing them. The investigation revealed that there was room for significant improvements in reducing delays and made recommendations to effect these improvements. However, the investigation was conducted prior to the Committee of Inquiry into the Sugar Industry and the findings of the Cane Transport Feasibility Committee (Rorich *et al.*, 1982; Eggers *et al.*, 1983) and incentives for implementing many of the recommendations did not exist. There have also been significant changes in the sugarcane transport system since the investigation and along with the proposed new cane payment system, these factors make a re-investigation of harvest-to-crush delays worthwhile.

The SICB investigation into harvest-to-crush delays (Brokensha *et al.*, 1975) identified many of the areas in the sugarcane harvesting and delivery system in which delays occur and also proposed some methods of altering the system to reduce these delays. However, it is very often difficult to estimate the effectiveness of changes to a system without actually implementing them. Furthermore, implementing changes can be very costly and time-consuming, especially if the changes do not have the desired effect. One way of estimating the effectiveness of making alterations to a system is to develop a model of the system, implement the changes in the model and then look at the effect of the changes on characteristics of the system that are under study - in this case the harvest-to-crush delays. In this way many different changes to a system can be investigated and their effectiveness can be gauged without the associated costs of experimentation with the real system. Furthermore, time can be controlled in a model - it can be compressed or expanded to allow the processes in a system to be studied. As a part of the 1975 SICB investigation into harvest-to-crush delays, Hoekstra (1975) developed a shift-by-shift simulation of cane movements, changes in stock levels and delay times for an idealised steady-state week of operation for the Amatikulu Mill in KwaZulu-Natal to investigate the effect of such factors as changing delivery and milling schedules, mill stoppages and irregular cane supplies to the mill.

Therefore, the aim of this project, which was proposed by the South African Sugar Association Experiment Station, was to develop a theoretical, computer based model of the various systems of harvesting and delivery of sugarcane used in the South African sugar industry. A literature review of techniques used to model harvesting and transport in various industries was thus conducted to determine the most appropriate technique for the situation of sugarcane harvesting and transport and the purposes of this project. Simulation modelling was chosen as the most appropriate technique. The simulation model developed was then used to investigate different proposed methods of reducing harvest-to-crush delays, look at where bottlenecks occur in the system and provide a holistic view of the overall system. The benefit of a holistic view of the system was to address the interests of both millers and growers who are often seen to be working against each other. Since the problems of one group affect the efficiency of the other in supplying cane, an investigation of the system as a complete entity was necessary to maximise the benefit to the industry as a whole and therefore to both groups.

According to Brokensha *et al.* (1975), many of the problems leading to excessive harvest-to-crush delays exist at the scale of a mill supply area, e.g. the differences between harvesting and delivery schedules and the milling schedule lead to buildups of stockpiles of cane in which the cane incurs delays. The model was therefore developed at the scale of a particular mill and the area of farms supplying that mill with sugarcane. The Sezela mill on the South Coast of KwaZulu-Natal was chosen as the mill area in which to conduct the study, since a simulation study of millyard operations which looked at turnaround times of trucks offloading in the yard, had already been conducted by Simulation Services cc (Schaller, 1997) and there was thus data readily available on millyard operations. Furthermore, the Department of Agricultural Engineering also has strong contacts in the area which ensured the availability of information on the harvesting and transport aspects of the cane supply system. The Sezela mill area produces about two million tons of sugarcane per annum which is approximately 10% of the total produced by the South African sugar industry.

In this dissertation a review is made of sugar cane harvesting and delivery systems and the factors influencing harvest-to-crush delays. A review is also made of techniques used to model harvesting and transport systems and the Arena simulation modelling system which was chosen as the simulation software package in which to develop the model. The collection of information on harvesting and delivery systems in the area, including a survey of farmers in the area is then detailed and the formulation of the model is described. The results of validation and experimental runs of the model are presented and discussed and the dissertation is concluded with a discussion of the implications and applicability of the results and the suitability of the methodology for application to other mill areas and harvesting and transport systems.

2. SUGARCANE HARVESTING AND DELIVERY SYSTEMS

For the purposes of this study the processes involved from the time that sugarcane is burnt or cut to the time it is crushed at the mill were investigated, since this is the period in which the quality of the cane deteriorates. There are many different systems of harvesting and delivering sugarcane and it was necessary that most of these systems would be able to be modelled with whatever tool of analysis was to be used if sensitivity analyses and 'what if' exercises were to be performed. In South Africa, harvesting is predominantly performed by hand but it was also necessary to be able to model mechanical harvesting as this was possibly a method by which the efficiency of the process could be improved and delays decreased. Similarly, it had to be possible to model the various types of transport that are used on different farms. The system as a whole is best visualised by the use of a flowchart (Figure 1). The information in Figure 1 and the following discussion was mainly derived from Meyer (1993).

2.1 General Description

In South Africa, sugarcane is usually burnt before being cut, mainly to remove the trash from the sucrose containing stalks and thus to make the cutting process easier. If unburnt trash is left on the ground, it also contributes to lower ground temperatures which affect the regrowth of ratoons. Burning is usually carried out in the early morning and late evening when conditions are less conducive to runaway fires. If conditions do prevent burning for long periods of time, the cane may be cut without first being burnt, but this practice is usually avoided, except in limited areas of the country. Once the cane is burnt, it is either manually or mechanically cut. These are the first steps of the process illustrated in Figure 1. After cutting, a number of different processes may occur, depending on the system that the farmer is operating. These processes can be visualised by tracing the various routes from cutting to loading into infield transport in the flowchart. If field conditions are suitable and the cane was mechanically cut it may be loaded directly by the harvester into infield transport such as a tractor with a basket trailer or a truck and trailer rig. Otherwise the harvester may windrow the cane for later stacking or directly stack it. The windrowed or stacked cane is later loaded into infield transport either manually or mechanically with a grab loader. The cane may be loaded either in bundles which are tied together with chains or as loose cane. A similar process happens with the manually cut cane.

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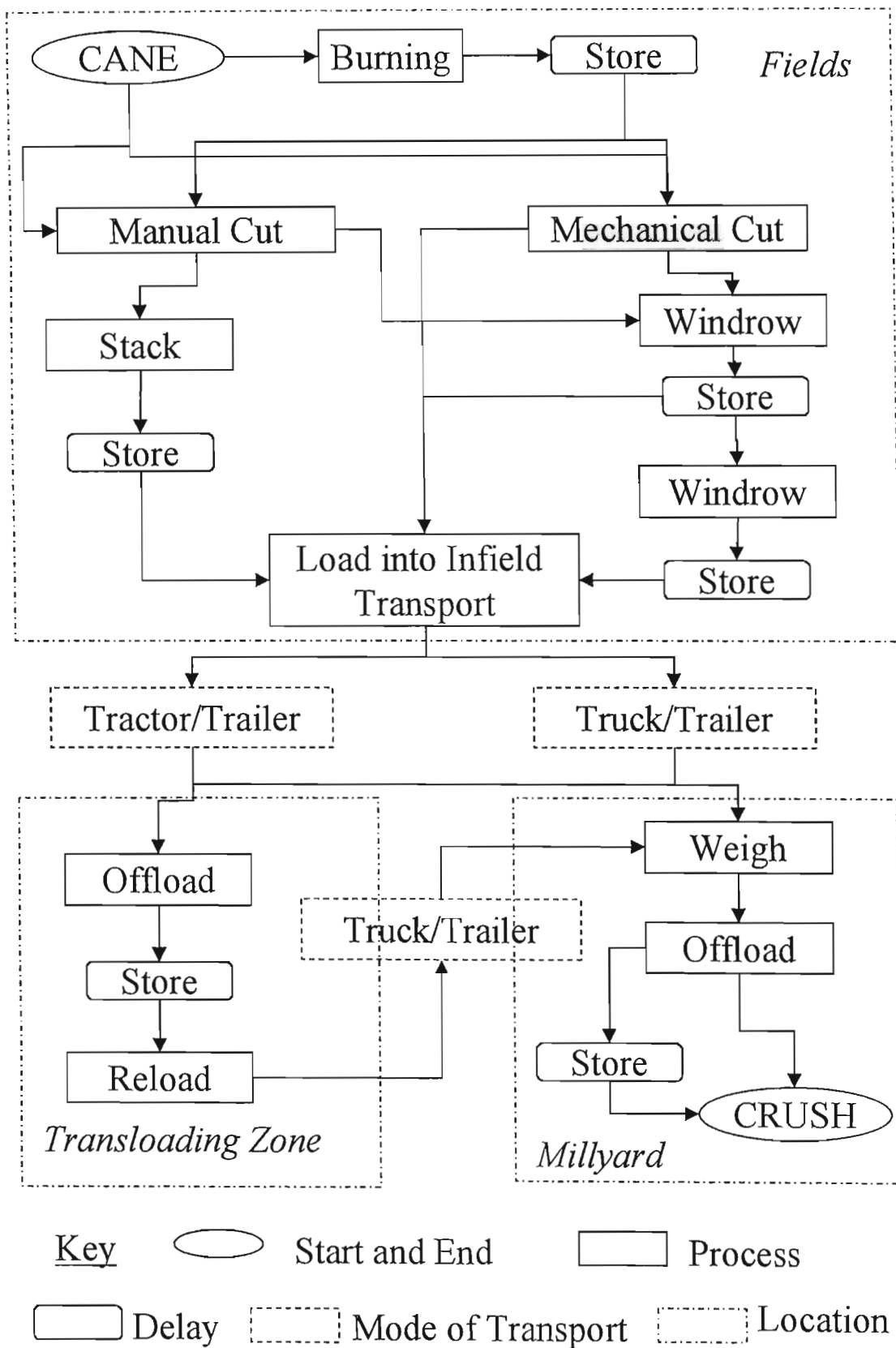
Figure 1. Flowchart of sugarcane harvesting and delivery systems in South Africa

The cane in the infield transport may either go directly to the mill if it is close enough or may be reloaded at a transloading zone into road transport, which is a rigid truck and trailer combination or truck tractor and trailer combination of one sort or another. These trailers may either be flat bed or hilo. Hilos are basket trailers that have chains attached to a lifter bar on one side that is raised with a crane at the mill to spill the cane out of the trailer. The various modes of transport are indicated by the dashed boxes in Figure 1. If the cane is bundled, the transloading operation is performed with a overhead gantry, scotch derrick or mobile crane, but if it is loose a pushpile or grab loader is used. The bundling chains are usually removed in the transloading process. There is also usually some stockpiling done at the transloading zone. Prior to the 1960's, much of the industry's crop was delivered to the mill by tramline trucks and South African Railways trucks. However, this practice has decreased in popularity due to the increasing cost and the inflexibility of rail transport.

At the mill the cane is weighed, while still in the transport, and then offloaded. If the cane is in bundles, it may be offloaded with an overhead gantry and then stockpiled to be crushed when gaps occur in the supply of cane. The gantry is also used to transfer the stockpiled cane to the feeder table for crushing. The other main method of offloading cane is to use a spiller gantry to spill loose cane directly onto the feeder table or onto a concrete floor for stockpiling.

2.2 Causes of Harvest-to-Crush Delays and Possible Improvements

The main sources of delay in the system occur where sugarcane is stockpiled. According to the Report on the Investigation into the Delays Between Harvesting and Crushing of Sugar Cane (Brokensha *et al.*, 1975) the following are causes of delays :

i) Overlap burning and burning of more than one day's supply of cane.
If new cane is burnt before all the cane from the previous burn has been cut, delays are incurred while the remainder of the cane from the previous burn is cut. This practice of overlap burning is used to provide a buffer stock of burnt cane that can be cut should conditions (e.g. rain or wind) prevent further burning. Furthermore, if more cane than can be cut in one day is burnt at one time, delays are also incurred since the cane starts deteriorating as soon as it is burnt and therefore the longer the burnt cane stands in the field, the worse the deterioration. There is resistance to

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daily burning because of the cost of cutting additional fire breaks, the increased likelihood of runaway fires and days on which burning cannot be carried out due to unfavourable conditions and the increased management required. These disadvantages have to be weighed against the benefits of improved cane quality facilitated by shorter harvest-to-crush delays. One possibility in mitigating these disadvantages is to introduce group harvesting so that if, for example six growers are in a group, each grower could burn and harvest his week's supply of cane in one day.

ii) Not despatching cane on the same day as it is cut.

This may occur if the schedule of burning and cutting prevents cut cane from being loaded and transported before the shift finishes. This forces an overnight delay which adds significantly to the overall age of cane reaching the mill. The actual delay depends on the system of harvesting that is used - generally if cutting and stacking are performed by separate groups and larger groups of labour are used, the despatching of the cane can start earlier in the day and more of the cane is despatched on the same day that it is cut. A major obstacle to this type of operation was the payment of labour on the basis of the weight of the bundles they constructed which meant that the cane could not be despatched before the bundles had been weighed. The use of a system whereby the labour is paid on the basis of row length cut overcomes the limitations of payment on weight.

iii) Stockpiling at the transloading zones.

Stockpiling is practised for various reasons, including maintaining deliveries when conditions (lack of labour or inclement weather) prevent cutting of fresh cane, being able to capitalise on open allocation days and allowing for unequal cutting and delivery days. This last situation occurs when cutting is conducted Mondays to Fridays while deliveries take place Mondays to Saturdays.

iv) Irregular milling.

Mill breakdowns have effects right through the cane transport system, causing delays in the field, at the zones and in the mill yard. The effects are particularly serious if the stoppage occurs during the night and the farmers are only informed of the cutback in allocation in the morning once cutting has already commenced. The effect of irregular milling can be seen from Figure 2 which shows graphs of weekly average delay, total percentage milling time lost (including stoppages due

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to cane shortages) and percentage milling time lost due to milling problems. This graph is for the Amatikulu mill during the 1974/75 season in which the mill had a particularly difficult year with its equipment and it shows the correlation between mill stoppages and delays particularly well. It can thus be seen that good communication between the miller and the growers is important in reducing delays.
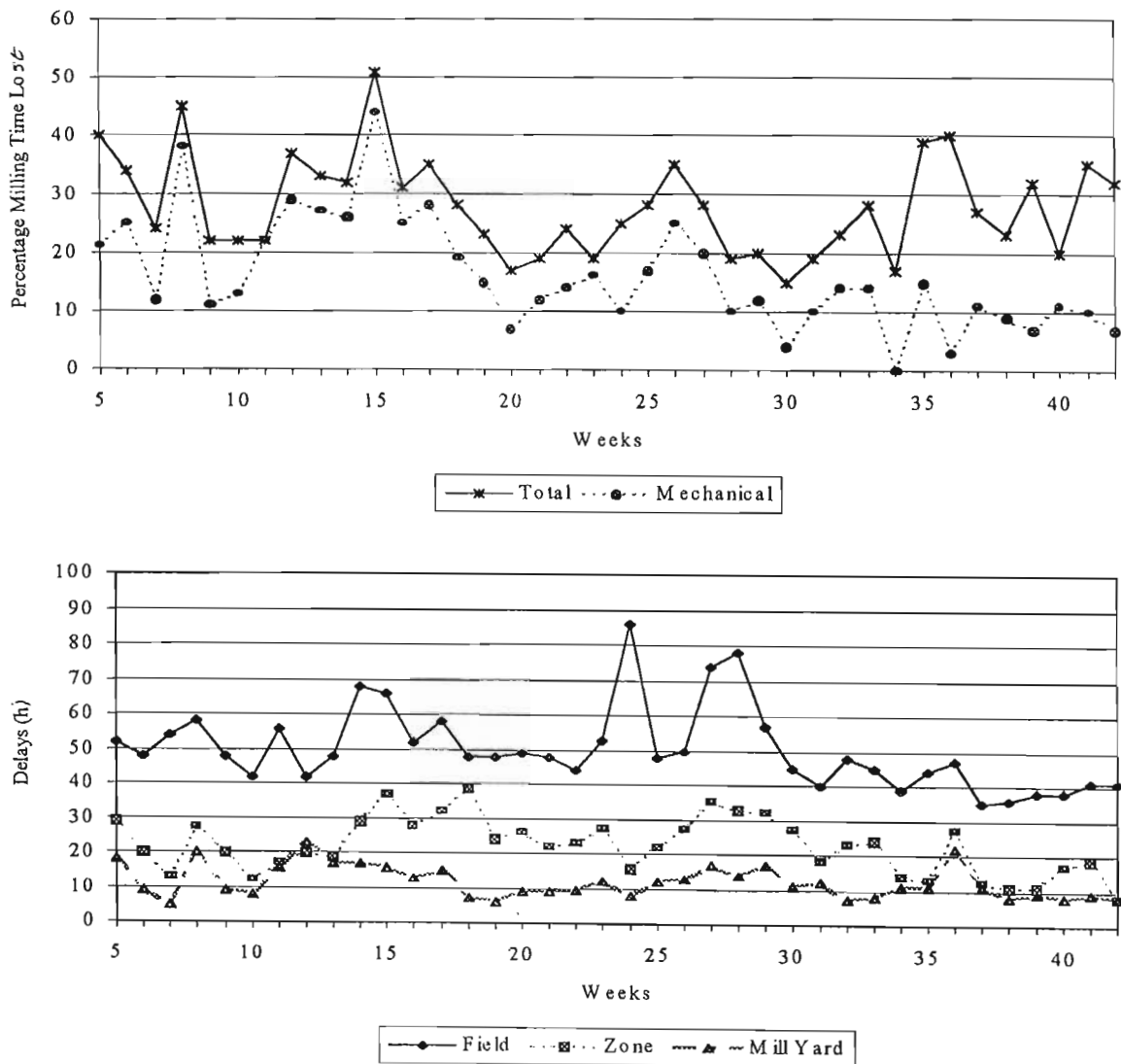
Figure 2.   Milling time lost and delays for Amatikulu mill 1973/74 season (after Brokensha *et al.*, 1975)

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v) High vehicle turnaround times.

If cane transport vehicle turnaround times at the mill are not kept to a minimum, the amount of cane that can be delivered on the same day that it is cut will be affected by the lack of vehicle availability. The effect is thus indirect as the delays will be caused by the cane not being delivered on the same day as it is cut rather than directly by poor turn around times.

vi) Differences between the milling cycle and the delivery cycle.

Since cane is dispatched from the fields over a period of 8 to 12 hours per day and the mill crushes 24 hours per day the flow of cane from the fields must be faster than the rate of crushing and the excess must be stored at the zones or mill until the mill is able to catch up. Furthermore, if the mill is running for longer than cane is being delivered each week, stocks must also be built up to supply the mill with cane once deliveries have ceased. The timing of the weekly maintenance stop at the mill is also important - if it is on a Monday, greater stocks also have to be kept since the mill will have to start crushing each day's deliveries later than if the maintenance stop were on a Sunday. Changing to a Sunday maintenance stop and crushing the cane in the same period that it is delivered in is not a simple matter since engineering staff do not like to work on a Sunday and crushing cane in a shorter period implies increasing the capacity of the plant which is a costly exercise.

Brokensha *et al.* (1975) concluded their report with a look at the systems operating in Australia as that country had very low harvest-to-crush delays, for which there were many reasons. Australian growers were permitted to burn, at most, sufficient cane for two days' deliveries at one time. Cutting times ran from 04h00 to 20h00, with each grower's hours of cutting having been staggered throughout the day and cutting and milling days being in step, running from Monday to Friday, with no week-end carry-over of chopper harvested cane. Furthermore, cutting and loading were conducted simultaneously and transport schedules and mill stockyard patterns had been organised to ensure that cane cut in a specific time interval was all milled before cane cut in the next time interval. However, even this system had room for improvement. Ridge and Dick (1985) examined the Queensland system of harvesting and transport and concluded that better harvester and transporter utilisation and increased harvesting group sizes were key factors in minimizing costs in sugarcane production.

Many of these procedures are obviously only possible due to the chopper harvesters used in Australia, but certain aspects of the system can still be applied to the South African situation. Firstly, cane could be despatched from the field on the same day as it is cut. This will eliminate night time and weekend carryovers. Secondly, group harvesting could be adopted as this will reduce average and maximum delays by making possible better organisation and scheduling of cutting and transport and, thirdly, milling could be brought more into step with cutting to eliminate weekend stock carry-overs (Brokensha *et al.* 1975).

A technique for modelling harvest-to-crush delays in the sugarcane harvesting and delivery system was therefore required so that methods of reducing these delays could be investigated. A review of techniques used to model harvesting and transport systems in various industries and their applicability to this project is presented in the following chapter.

3. REVIEW OF MODELLING TECHNIQUES

Management science or systems analysis can be defined as the application of the scientific method to the analysis and solution of managerial decision problems (Turban and Meredith, 1981). The tools of systems analysis or management science have been used in industry for several decades, particularly by industrial engineers in the manufacturing environment. These tools may involve the use of some manner of model, (a representation of the system being analysed) which is utilized in experimental investigation to yield design or operational decisions at less cost and in less time than direct manipulation of the system itself (Blanchard and Fabrycky, 1981) or they may be an optimization algorithm. Included in these tools are the techniques of Linear Programming, Scheduling, Queueing Models and Simulation Modelling, which will be examined here with respect to the systems of sugarcane harvesting and transport.

Management policies in freight transportation systems can be divided into three *planning levels* (Crainic and Laporte, 1997). These levels are : *Strategic* (long term) planning involving the highest level of management and requiring large capital investments over long time horizons, *Tactical* (medium term) planning aiming to ensure, over a medium term horizon, an efficient and rational allocation of existing resources in order to improve the performance of the whole system and *Operational* (short term) planning performed by local management in a highly dynamic environment where the time factor plays an important role and detailed representation of vehicles, facilities and activities are essential. The problem of harvest-to-crush delays in sugarcane transportation seems to require attention at all three levels of planning as both infrastructure and management practices may have to be changed to facilitate improvements and the time factor is particularly important.

3.1 Linear Programming and Scheduling

The transportation problem is a special class of linear programming problems. It deals with shipments from a number of sources to a number of destinations. Typically, each source is supply limited, each destination has a known demand and the shipping costs between sources and destinations are given. The object is to find the cheapest shipping schedule that satisfies demand without violating supply constraints (Turban and Meredith, 1981). The transportation problem

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is usually solved by means of the transportation method, which is a search and evaluation algorithm, because of the great computational effort involved in solving it directly as a linear programming problem. Scheduling usually involves finding feasible combinations of vehicles, routes, loads and times to ensure a coordinated use of a fleet of transport vehicles. In the forestry and sugar industries it is also useful to ensure that the vehicles arrive at the mill in a steady stream if traffic congestions and product stockpiles are to be avoided, since the mills usually process the product at a steady rate. Scheduling is best used where there is some sort of centralised control of the transport fleet such as in the case of a haulier transporting cane or a forestry company with its own fleet of trucks.

Network programming, which is a form of the transportation problem, has been used in the scheduling of log trucks in the forestry industry. Shen and Sessions (1989) used an algorithm called the 'out of kilter' algorithm to minimize transport costs from log landings in the forests to the mill. Truck departure and arrival times and fleet requirements were derived from examination of the network solution. This same 'out of kilter' method was used by Oduwole (1995) to perform 'non-stochastic scheduling coordination' in his analysis of multimodal transport network systems for the implementation of Intelligent Vehicle and Highway Systems. Crainic and Laporte (1997) review various operations research models for solving freight transportation problems at the three planning levels mentioned in the introduction to this chapter. These models are generally specific to a particular level of planning and are network based, involving optimization techniques.

The use of linear programming in transportation problems, however, has its limitations. Sinclair and Van Dyk (1987) report that attempts to formulate a combined routing and scheduling problem as a mixed integer linear programming problem met with little success. The problem was described as a tractor-trailer problem which involved the daily scheduling and possible minimization of the number of vehicles used for a company responsible for the road transportation of all the containerized cargo in certain restricted regions. The resulting programming problem for the 132 vehicles, 1100 movements and 400 clients had one million integer variables and two million continuous variables. These are the variables which had to be solved for to find an optimal solution. A heuristic procedure which involves a set of rules

governing a trial and error process was thus developed to find satisfactory solutions to the problem. Crainic and Laporte (1997) also report that many researchers use heuristics when solving stochastic vehicle routing problems.

The use of heuristic procedures in scheduling problems is fairly widespread. As early as 1968, "simple scheduling" was used to improve utilization of rolling stock used for transport of sugarcane in Queensland, Australia and to reduce the delay between loading cane in the field and crushing it at the mill (Murry, 1968). In South Africa, a scheduling board was used at the Tongaat sugar mill to control the heavy vehicle fleet transporting cane between the transloading zones and the mill (Dent, 1973). This resulted in the reduction of queueing in the mill area and improvements in rateable deliveries to the mill. McIntosh (1985) described the sugarcane scheduling system used at the New South Wales Sugar Milling Co-operative - Broadwater and also emphasised the importance of coordinating the scheduling of all phases of the transport operation. He stated that, if one stage is restricted, other stages will be affected as a result and emphasised that the mill is part of the cane scheduling link and that its performance contributes to the requirements and performance of harvesting groups and their personnel.

In the forestry industry too, scheduling methods that do not involve optimisation have been widely used. Robinson (1994) evaluated the theory of log truck scheduling and despatching for the New Zealand forest industry and found that it was impossible to find optimal schedules but that there were methods for finding satisfactory feasible solutions. A method was proposed whereby optimal schedules were determined for single trucks using a tree search procedure until the whole fleet had been scheduled (The Greedy Method). This method worked on the assumptions that total queueing time was zero and the time required for any operation could be predicted exactly. A simulation was used to ensure that the schedule would work in practice by including queues and random factors. In South Africa, Mondi Forests use the ASICAM system for the scheduling of their truck fleet (Crickmay ,1997). The system is a simulation model that attempts to replicate the scheduling that would occur in reality, given the volume of products that have to be hauled from origin to destination and the trucks available (Weintraub et al., 1996). Truck assignments are made on the basis of a set of heuristic assignment rules, the trucks are loaded and despatched and, after they are unloaded at the destinations, the trucks are assigned new trips. In this manner the scheduling for a complete day's operations is completed. The heuristic

assignment rules are based on regularity of arrivals to destinations, a trip desirability index calculated on trip cost and a congestion penalty, and the priority of individual trips. Thus, although ASICAM does not calculate an 'optimal' schedule, it contributes to significant savings through improved coordination of transport operations and the existence of a system of checking the performance of the haulier (Crickmay 1997). Sappi Forests use a similar system for their scheduling that is rule based and emphasises standards, despatching and control or measurement for utilisation based haulier contracts (Hunter, 1997). The program, called *Woodtrak*, was developed in-house and utilises a Global Positioning System (GPS) to keep track of rigs and allow for continuous communication between drivers and shift controllers who update scheduled trips.

3.2 Queueing Models

In situations where a 'service' is required by a number of 'customers', a waiting line or queue will develop if service capacity is less than maximum demand. Since the building, operating and maintenance of a service facility to meet all demands, all the time is usually prohibitively expensive and, in most situations, it is practically impossible to constantly adjust the capacity of a service facility to fit demand, such facilities will be designed with a capacity less than maximum demand. Therefore, at certain times, customers might have to wait in a queue while at other times they may be serviced immediately or the service may be idle. The problem of determining the appropriate level of service is addressed by the technique of *queueing theory* (Turban and Meredith, 1981). This theory may be applied to the situation of sugarcane transport if the sugarcane is viewed as the customer and the transportation facilities are viewed as the service facilities.

A queueing system is composed of a number of parts. The customers are defined as the entities in need of service and are drawn from a population or source. This source may be infinite (e.g. people visiting a bank) or it may be finite (e.g. when a repair crew in a factory is responsible for maintaining a number of machines). The arrival process or the manner in which the customers enter the service facility is the next part of the system. Customers may arrive in batches or as individuals and may arrive on a scheduled or unscheduled basis. If arrivals are unscheduled, a frequency distribution of either the mean arrival rate or the mean interarrival time is used to

describe the arrival process. At arrival the customers join a queue if the facility is busy. The queue discipline involves such concepts as first in first out and priorities. The time consumed by the service given in a facility may be constant or fluctuating. If it is fluctuating, the time may be described by a frequency distribution of either the length of service or the service rate. Equations are developed for measures of performance based on the various possible types of queueing systems. (Turban and Meredith, 1981)

Whitney and Cochran (1976) adapted queueing theory developed for construction operations to the Louisiana cane harvesting and transport system to predict the delivery rate of cane to the mill. The system consisted of a loader or chopper harvester and a number of transport units which arrived at the field and either began loading or waited in a queue. When loaded the transport units travelled to the mill, offloaded and returned to the field. This theoretical analysis was combined with the results of a simulation model to relate the effect of the major components of a transport system on delivery rate by a nomograph. This analysis was however for a relatively simple situation of one harvester or loader and a number of transporters.

Koger (1992) used queueing theory to analyse skidding, loading and trucking interactions in timber harvesting. The technique was used to determine arrival and departure rates, the probability of trucks having to wait before being loaded and the optimum number of trucks to use. Once again this analysis was for a relatively simple case of a single loader at a single landing and was used in conjunction with simulation.

3.3 Simulation Modelling

Simulation involves the modelling of a system as it progresses through time and is particularly useful for modelling queueing structures which describe a wide variety of systems (Robinson, 1992). Simulation modelling has been used, particularly in the manufacturing environment, since the early 1960's. The basic principle is that the analyst builds a model of the system of interest, writes computer programs that embody the model and uses a computer to imitate the system's behaviour when subject to a variety of operating policies. Thus, the most desirable policy may be selected. Simulation models are usually classified either as discrete event, in which case the

model variables are only of interest when a change occurs in the system, or continuous in which case the value of the variables change continuously as the simulation proceeds (Pidd, 1992).

Simulation is usually used when the problem under investigation is too complex to be treated by analytical models such as queueing theory or by numerical optimization techniques such as linear programming (Turban and Meredith, 1981). Although simulation is one of the most widely used and accepted tools of systems analysis, it is imprecise and provides only statistical estimates rather than exact results (Lee, 1978). This is because the variables used in simulation models are generally represented by standard or non-standard distributions and as such, the model may have to be run numerous times to get reliable results. Not all simulation models utilize stochastic variables (Benock *et al.*, 1981 and Semenzato, 1995), but the ability to incorporate stochastic processes is one of the strengths of simulation modelling. Another important feature of simulation models is that they do not provide any form of optimization - only one setup of a system at a time can be investigated with a simulation model and the results of a number of different setups have to be compared to determine which is the best, which will not necessarily be the optimum.

3.3.1 Simulation software and its applications

Hoekstra (1973) used a 'computerised Monte Carlo procedure' to predict the effect of mill stoppages on cane transport fleet utilisation for a cane handling facility using a spiller offloader. The Monte Carlo procedure could be described as the basis of simulation since it simulates the operation of a process by randomly picking out values for variables such as inter-arrival times and service times in accordance with the appropriate probability distributions and lets these times interact in a logical and realistic manner. Hoekstra used a simulation language to code the algorithm describing the events occurring during a mill stoppage and control the running of the simulation. There are numerous such languages available e.g. GASP IV, SIMSCRIPT and SIMAN. These languages have a number of common features - a hidden executive to perform the sequencing and scheduling tasks which underlie any discrete event simulation, a well suited syntax to ease the process of simulation modelling, variable tracing and data collection for debugging and analysis purposes and a control shell within which the simulation may be run to carry out experiments (Pidd, 1992).

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The GASP IV simulation language was used by Lee (1978) to model the sugarcane supply system in Jamaica. A functional flow chart of the GASP IV programme used by Lee is shown in Figure 3. Lee was also concerned with cane deterioration or 'stale' cane and thus used his model of a loader, trailer and tractor system to investigate methods of improving the efficiency of the system. He looked at reducing the variability of loading time per wagon, controlling the placements of wagons to reduce the variation of the travel time of the infield tractor to and from the loader, and operating two road haulage tractors along with more than eight wagons for travel distances greater than one and a half kilometres to the factory.

However, a simulation language is not the only way of coding a simulation. Simpler situations can be simulated using a spreadsheet package. As a part of the report on the delays between the harvesting and crushing of sugar cane (Brokensha *et al.*, 1975), Hoekstra performed a shift-by-shift simulation of the cane movements, changes in stock levels and delay times for an idealised steady state week of operation for Amatikulu Mill (Hoekstra, 1975). This simulation was performed in a tabular format but was later put onto a Quattro Pro spreadsheet (Hoekstra, 1997). Since this was a shift-by-shift simulation, the time steps were in 12 hour intervals and the simulation was thus fairly coarse. However, it still gave some fairly good indications of the effects of different operational conditions such as putting more hilos onto spiller, shortening the weekly hilo transport programme, irregular cane supplies to the mill and mill stoppages. The simulation also did not include the effects of random factors since all the transport and other times were taken as constants.

Another method of developing a simulation model involves using a general programming language to code the simulation algorithm. This method may be used where the cost of the simulation software package is a consideration or a highly specific and fast-running model is required, but has numerous disadvantages, including the time and cost involved in developing the model and the detailed programming skills required. Another consideration is that many of the tasks performed in a simulation are common to all simulation programs and pre-written libraries may therefore be used to perform general simulation tasks. This may still leave the programmer with the disadvantage of having to write the logic and other application specific features in a language which may not be suited to simulation (Pidd, 1992). An example of such a program is STALS-3 developed by Koger (1992) to analyse timber harvesting systems as mentioned in the

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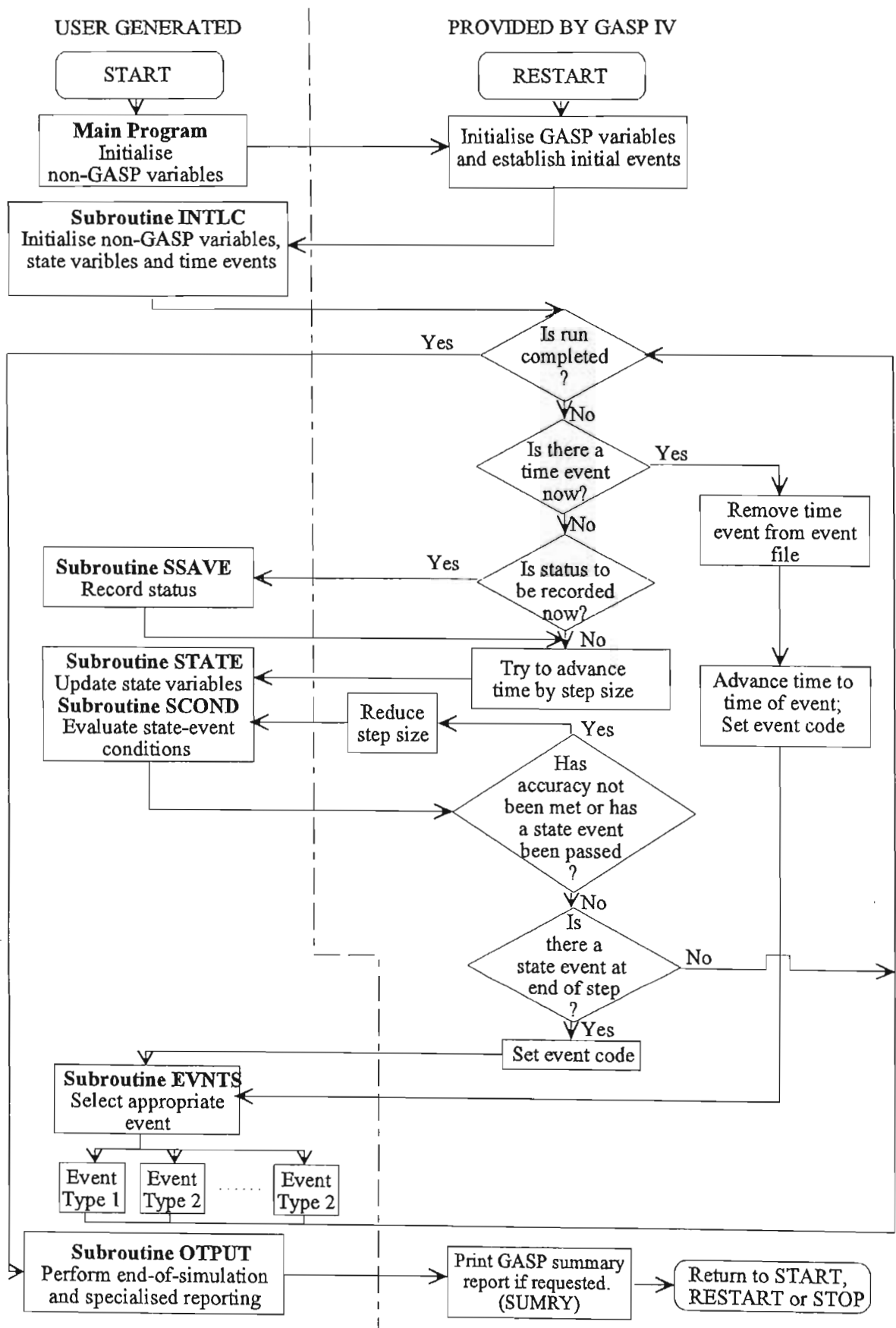
Figure 3.   Functional flowchart of the GASP IV programme (after Lee, 1978)

queueing models section. The program was written in Microsoft QuickBASIC and was designed to run on an IBM compatible PC. The simulation portion of the program was used to determine equipment delays and the effect on harvesting costs of the dynamic interaction of equipment delays, full landing conditions and wood shortages. An example of the simulation output from the STALS-3 program is shown in Table 1. These results could be used to make decisions about landing sizes and skidder and trucking rates.

Table 1.   Simulation output (after Koger, 1992)

	Skidding	Trucking	Total
Number of delays	10	70	80
Delay time (h)	13.64	22.21	35.85
Delay time (%)	11.36	18.14	
No of cycles	419	95	514
Sum cycle time (h)	120.6	122.4	242.52
Prod./8h day (Board Feet)	8328.90	8166	
Min vol/cycle (Board Feet)	155.17	1016.88	
Avg vol/cycle (Board Feet)	298.33	1315.79	
Max vol/cycle (Board Feet)	462.27	1610.24	
Min cycle time without delays (h)	0.000	0.004	
Avg cycle time with delays (h)	0.028	1.276	
Avg cycle time without delays (h)	0.254	0.976	
Max cycle time without delays (h)	1.886	4.146	
Sum delay costs ($)	296.49	1463.10	1759.58
Delay cost/unit ($)	0.00237	0.01170	0.01408
Sum delay & working costs ($)	2610.19	8067.16	10677.34
Delay & working cost/unit ($)	0.02088	0.06454	0.08542

The General Purpose Simulation System (GPSS) was used by Libunao and Lantin (1977) to simulate the sugarcane transportation system in Northern Leyte in the Phillipines. GPSS uses a activity cycle diagram to describe the system which is then read as data by the program. This then is a form of simulation software that is based on a graphical approach instead of a spreadsheet or programming language approach. This model took into account stochastic variables such as weather and equipment breakdowns as well as travel, queueing, service and unloading times. The results of the model were then used to make management decisions about such factors as truck cycle times and required fleet capacities.

The final class of simulation software investigated is visual interactive modelling and simulation systems. Many simulation languages have facilities for providing some sort of graphical representation of the model as it is run. These languages are called visual interactive simulation systems - an example is the SIMAN language with its CINEMA animation facility. The SIMAN/CINEMA system was used by Semenzato *et al.* (1995) to simulate sugarcane harvesting operations on an agro-industrial co-operative farm at Cartavio, on the northern coast of Peru. The simulation was used as a basis for a Decision Support System (DSS) for addressing the following:

i) given certain resources for cutting, loading and unloading, what is the maximum area of a field of standing cane, as a function of distance from the mill that should be burnt at one time so that it can all be processed within 15 days?

ii) for a given size of field and distance from the mill, what are the minimum resources needed in order to process all the cane in the field within 15 days?

The simulation was also used to provide information about queues formed during loading and unloading, and the utilization of resources.

Visual interactive modelling systems (VIMS) use a graphical user interface as a fundamental part of the modelling process. They are usually based on a network through which entities are assumed to flow from node to node. The word entity is a generic term used to denote any person, object, or thing—whether real or abstract—whose movement through the system may cause changes in the state of the system. At the nodes the entities are delayed as they are engaged in activity with whatever other entities or resources are placed on that node. VIMS are usually focussed on particular application domains, most commonly discrete parts manufacturing, and thus have terminology appropriate to their intended domain. (Pidd, 1992) The ARENA package is an extension of the SIMAN/CINEMA software into the area of VIMS. ARENA has been used to model the cane transport operations of Cargo Carriers at the Komati Mill in the Eastern Transvaal. The model was used to determine the best scheduling strategy for trucks transporting cane from the farm to the mill and to determine if these trucks could not be more fully utilized (Klein, 1997). At the Sezela mill, the ARENA package was used to model the operation of the millyard to determine if truck turnaround times and congestion in the millyard could be decreased (Schaller, 1997).

3.3.2 Other considerations

Recently there has been a shift in thinking in the simulation of transport systems to the use of more 'data-driven' models which can be applied to more varied situations and that are easier to use and do not necessarily require simulation skills. Different transport systems can easily be accommodated by simply changing input data. Cochran and Lin (1989) developed such a model for use in a transportation research project - the Arizona Freight Network Analysis (AFNA). The SLAM-II simulation language was used and a "link-based conditional probability branching discrete-event model" was developed. A network of nodes and links was used to describe the system and trips were generated in this network by a number of probability distributions. The first distribution determined which nodes the trips were generated at, the second distribution determined which link to take from the node and the third distribution, serving for the conditional-branching routeing logic, determined the percentage of trips branching to all outgoing links or terminating at a node for each incoming link. By changing these distributions, changes in the transport network can be modelled and their effects can be predicted. The model was used as the core element of a DSS that included a database to organise and preprocess mail survey and topology data and a user-friendly menu structure which assists in both data manipulation and interpretation of simulation experiment output (Cochran and Chen, 1991). The DSS was used by the Arizona Department of Transport for planning and to study the impacts of anticipated increases in freight flows in the Arizona highway system.

A similar approach was adopted by Kondratowicz (1990) in developing a simulation methodology for intermodal freight transportation terminals. He also used a data-driven approach that treats data and control logic as distinct parts in modelling seaport and inland terminals in intermodal transportation systems. The TRANSNODE simulator can be used to model transport of cargo into and out of a terminal by truck or rail, cargo handling facilities such as storage and cranes and the import and export of bulk cargoes by ship. The conventions of the simulator in describing these various elements of the system allow any transportation terminal or group of interconnected terminals, large or small, multipurpose or specialized to be modelled at optional scale. The simulator was expected to be used in the industry for supporting strategic and tactical decisions and by engineering firms in evaluating designs and policies. Although these particular situations may not be directly applicable to the situation of cane transport, the concepts of the applicability

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of a model to various situations and the needs of the proposed users of the model should be an important consideration in the development of a model to simulate transport operations.

3.4 Choice of Modelling Technique

Some of the limitations of linear programming in transport problems have already been mentioned - any reasonably realistic representation of a system tends to produce problems involving large numbers of variables. Furthermore the formulation of linear programming problems can be very complex, requiring a good background in applied mathematics and this is not an advantage when trying to ensure credibility of the model with the people who will be using it and who may not have such a background. Heuristic scheduling techniques also have their limitations. By their very nature schedules are usually determined at the beginning of the schedule period and as such do not cope well with unexpected events. Conditions such as rain preventing transport getting into the fields may disrupt a whole schedule. Scheduling systems also have no facility for testing out the performance of different transport systems and comparing them to make design and planning decisions. Finally they do not account for random factors and problems that may develop as a result of these factors such as queues and breakdowns.

Queueing models are generally limited in the situations that they can cover. For example, if the interarrival times or the service times are not of a standard distribution, or if the setup and number of service facilities is too complicated, it may not be possible to analyse the system with queueing theory. This is likely to be the case for the fairly complicated system of 'facilities' and delay characteristics that exist in the South African sugarcane transport situation. There is also only limited evidence of the use of queueing models in the field of transportation modelling.

There are various advantages associated with the technique of simulation modelling. Simulation models are well suited to complex systems where there is interaction of different processes which cannot necessarily be described deterministicaly because they are able to model the individual processes and let them interact in a logical and realistic way. Simulation can also cope with dynamic and transient effects since it models a system as it progresses through time. Discrete event simulation models are particularly well suited to systems which can be described as combinations of processes and queues. Simulation models are useful in gaining understanding

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of systems as they force model developers to think about the operation of the system and thus possibly come up with alternative solutions to problems. They are also useful in communicating the details of systems and problems with systems to system users because simulation models can very often be grasped easily and quickly by non-experts, particularly where Visual Interactive Simulation is used.

There are of course disadvantages to the use of simulation models. Expertise in the principles of simulation modelling is necessary if a valid model is to be created. Even if a Visual Interactive Modelling System, which does not require knowledge of a programming language, is used, the developer of the model has to be aware of the principles behind the software and be able to design statistically valid experiments and interpret the output of the experiments. The high cost of simulation software investigated in this project, and the time that may be spent in developing a model, were also problems that had to be considered when deciding whether or not to use simulation to solve the problem.

Overall, however, the advantages of simulation modelling for cane harvesting and transport were deemed to outweigh the disadvantages, particularly if a certain amount of forethought and care was exercised in the use and development of the model. Another factor in favour of the use of simulation modelling for the cane harvesting and transport system was the considerable amount of work that had been done previously in this field. From the literature reviewed there had been more simulation modelling than any other type of modelling done of sugarcane transport. There was also a good local availability of expertise in the simulation modelling. It was thus concluded that simulation modelling is the best technique for the purposes of the modelling of sugarcane harvesting and delivery.

The Arena modelling system (Pegden *et al.*, 1995) was chosen as the simulation software package in which to implement the model because it has been used in the modelling of sugarcane harvesting and delivery systems previously, as a visual interactive modelling system, would require less time and effort in which to develop the model and had a reputation as being a versatile modelling package with good backup services available.

3.5 The Arena Modelling System

The Arena modelling system is based on the SIMAN V/Cinema V simulation language and utilises a flowcharting methodology for depicting system logic. The flowcharts represent the network through which the entities that interact with the system resources flow. The software takes the flowcharts which are constructed in the Arena graphical user interface and automatically generates the underlying SIMAN/Cinema model which actually runs the simulation. The SIMAN/Cinema model is divided into a model component which describes the physical elements of the system and their logical interrelationships and an experiment component which specifies the experimental conditions under which the model is to run, including elements such as initial conditions, resource availability, type of statistics gathered and length of run. Because the experimental conditions are specified seperately to the model description, they are easily changed without modifying the basic model definition. Once the model and experiment have been defined, they are linked and executed by the software to generate the simulated response of the system.

The Arena modelling system provides facilities for animation of the simulation as it is run. Animation constructs such as transporters, resource icons, variable displays and conveyors are provided and linked to the modules of the logic flowcharts. Animations of models make the debugging process easier and also provide a tool for communication of results. The Arena software also provides some error checking functions as well as an input analyser program that can be used to generate frequency distributions from historical system data and an output analyser program that can be used to graph and perform statistical analyses on the output generated by simulation runs. Microsoft Excel spreadsheets can be used to input data for Arena models and Visual Basic macros can be written to automate some tasks in Arena models such as importing data from various file formats and placing modules for different simulation run setups.

The collection of information about harvesting and delivery systems in the Sezela mill area required to construct a simulation model using the Arena modelling system is detailed in the following chapter.

4. DATA COLLECTION AND ANALYSIS

Apart from the general structure of harvesting and delivery systems in the South African sugar industry detailed in Chapter 2, it was necessary to collect information on the specific systems used in the Sezela mill area in which the study was to be conducted. Since there was no formal documentation available, this information had to be collected from a number of different sources.

4.1 Interviews and Mill Records

General background information was primarily collected by interviews with mill, haulier and extension personnel in the area as well as with growers. More detailed data with regard to delivery schedules and daily required deliveries (DRDs), haulage distances and zone loading types for particular farms were extracted from existing mill records. Zone loading type is either bundle or grab, according to whether some type of crane is used to load bundles or a bell grab loader loads loose cane in the transloading zone.

Informal interviews were conducted with the following people to collect information on the harvesting and delivery systems used in the Sezela mill area:

Mr Allan Simpson, Cane Procurement Manager, Illovo Sugar

Mr Bruce Irons, South African Sugar Association Extension Officer, South Coast Area

Mr Kevin Cole, Sugarcane grower and Agricultural Engineering Consultant

Mr Eric Arde, Field Manager, Illovo farms

Mr Anthony Domleo, Field Manager, Inkanyezi small growers

Mr Perumal Chetty, Operations Controller, Unitrans Sezela Depot

Mr Simpson provided most of the data from the mill records as well as information on millyard operations and contacts with a number of the other people interviewed. Mr Irons and Mr Cole provided information on private grower operations while Messrs Arde and Domleo provide information on the Miller-cum-Planter farm operations and Illovo Sugar backed Inkanyezi small grower operations respectively. Mr Chetty provided information on the haulage and, in particular, the dispatching operations conducted by Unitrans.

4.2 Millyard Simulation Study and Time Studies

Detailed data on millyard operations were derived from the simulation model of the Sezela millyard developed by Simulations Services cc for Illovo Sugar in 1997 and made available by Mr Simpson. This data included operating rules as well as frequency distributions for process times for the various operations occurring in the millyard, which were estimated from time studies conducted by mill personnel. In 1998, a new gantry crane was installed in the millyard for which further time studies had to be performed to determine the process times involved in its operation. Assistance with the time studies was provided by Andrew Simpson, a second year agricultural engineering student doing vacation work for Illovo Sugar at Sezela. The time study data was analysed by constructing frequency distributions which were used to estimate triangular distributions to describe the process times required.

4.3 Grower Surveys

As the model was developed, it became apparent that more detailed data were required on the harvesting and transport systems used on individual farms. Since there was very little existing data available in this area, it was decided to perform a survey of growers in the Sezela mill area to obtain a sample of the required information. The main emphasis of this survey was to collect data on numbers of infield transport and loading equipment and systems and schedules of burning and harvesting used on different farms. However, other data, such as the growers' estimates of the delays incurred at various points in their harvesting and transport systems and perceptions of the causes of harvest-to-crush delays, were requested if the grower was able to provide it.

The survey was conducted by visiting individual growers with a standard questionnaire form and filling out the form with them. The questionnaire form is shown in Appendix A. Some sections of the questionnaire, for example schedule 3, were not well completed, mainly because the farmers did not have records of the data required. Also, the farmers' estimates of burn to cut and cut to dispatch delays proved to be of limited use. Initially, a group of 20 growers was surveyed, with the growers chosen to get representation of as wide a range of harvesting and transport systems as possible. Assistance with these grower interviews was once again provided by Andrew Simpson, doing vacation work for Illovo Sugar.

After consultation with Mr Harvey Dicks of the Statistics and Biometry Department at the University of Natal, Pietermaritzburg, it was decided to group the farms in the area on the basis of farm size and whether the farms use haulier or own transport. On the basis of these groupings it was decided that further surveys were needed in certain groups and further interviews were therefore performed in the same manner as for the initial 20 interviews.

The groupings into which the farms were divided are shown in Table 2, along with the numbers of farms in each group, the number of surveyed farms in each group and the tonnage supplied to the mill by each group per annum. Although only 28 individuals were interviewed, these individuals represented 60 farms in the area with separate quotas, since many growers own and manage more than one farm and some of the individuals interviewed were harvesting contractors who perform harvesting for a number of farms. It can be seen that the percentage surveyed in most groups is reasonable, except for in the haulier transport - medium scale group. However, the percentage tonnage that this group supplies to the mill is very small.

Table 2. Farm groupings for grower survey

Own/Haulier Transport	Scale	No. Farms	No. Surveyed	% Surveyed	Annual Tonnage	% Tonnage
Own	Quota	22	10	45	437000	21
	Small	19	7	37	45000	2
Own Total		41	17	41	482000	24
Haulier	MCP	10	4	40	532000	26
	Quota	31	19	61	511000	25
	Small	62	18	29	120000	6
	Small Groups	14	2	14	354000	17
	Medium Scale	14	0	0	50000	2
Haulier Total		131	43	33	1567000	76
Area Total		172	60	35	2049000	100

The data from the survey were then used to predict model parameters such as schedules used and numbers of infield transport and loading equipment for non-surveyed farms. The predictions were based on simple linear regressions based on data known for all farms such as DRD and zone loading type or discrete distributions when there was no relationship to known data. The actual relationships derived are set out in Chapter 6, where the inputs used for the existing situation model runs performed to validate the model are detailed.

The use of this data collected on harvesting and delivery systems used in the Sezela mill area, in developing the model and formulating experiments to perform on the model, is described in the following two chapters.

5. MODEL FORMULATION

As is mentioned in the introduction, the model of sugarcane harvesting and delivery systems needed to be developed at the scale of a particular mill and the area of farms supplying that mill with sugarcane. The scope of operations that needed to be included in the model was from the time that the sugarcane is burnt or cut to the time that it enters the mill to be crushed, since that is the time period in which the deterioration of cane quality occurs. Furthermore, the basic time unit that needed to be examined in the model was taken to be an hour because cane deterioration occurs over days and therefore, any additional delay less than an hour is likely to have minimal effect on the quality of the cane. Similarly, any process that does not have a significant effect on the overall harvest-to crush delay and that, by its exclusion, does not lead to an inadequately realistic representation of the system can be ignored. These principles were the basis for the conceptual model of the system from which the actual model could be structured and coded using the Arena flowcharting methodology. A description of the development of the model was presented in Barnes, Hansen and Lyne (1998). Before a conceptual model of the system could be developed, however, it was necessary to make sure that the actual system was fully understood.

5.1 Description of the Sezela Mill Supply Area

The Sezela mill cane supply system, which was chosen as the study area can be divided into two main sections of interest. Firstly there is the harvesting and transport section which includes all infield operations from burning onwards as well as transport from the fields to the transloading zones, transloading and transport from the zones to the mill. Secondly there is the millyard section which involves weighing the trucks in and out and offloading, stockpiling and feeding the cane into the mill.

5.1.1 Harvesting and transport operations

The Sezela mill, has three main classes of growers supplying cane as shown in Table 3 below.

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Table 3. Grower classes in Sezela mill area

Group	Tonnage Supplied/Annum
Mill-Cum-Planter (MCP)	550000
Private Commercial Growers	1160000
Small Growers	420000
Total	2130000

The Miller-Cum-Planter (MCP) group consists of 10 sections or farms owned by the milling company, Illovo, each of these sections having farm managers who are overseen by a field manager. Six of the farms employ a separate cutting and stacking system where the labourers are paid on the basis of ropes completed while on the other four farms, both operations are performed by each labourer who is paid on the basis of the mass of the stacks he produces which are weighed using a load cell on the transloading zone. Each MCP farm uses a combination of self-loading-offloading trailers and Bell loaded tipping bin trailers to remove cane from steeper and flatter areas of the farms respectively. The individual farms are remote from each other and each farm has its own harvesting and infield transport equipment, but the equipment is shared between farms in emergencies, e.g. when there is a runaway fire on one farm and a large amount of cane has to be cut on that farm. All the MCP farms use Unitrans, the major haulier in the area, to transport their cane from their transloading zones to the mill on Tuesday to Sunday nights.

In the private commercial growers' group there are approximately 53 individual farms, however, a number of these farms are grouped into combinations which very often include one or two small growers so that there are about 45 combinations in the area. Methods of harvesting and transport vary from farm to farm and some growers provide their own transport to the mill while others employ a haulier. Most of these growers deliver during the day, Monday to Saturday. However, some deliver at night or 24 hours a day and either Tuesday to Sunday or 7 days a week. All growers transload their cane.

The small growers are usually divided into areas in which harvesting and transport of the cane is conducted by a number of contractors. For example, there are 5 areas which are supported by the Inkanyezi company, which is a part of the Illovo group. These areas consist of 800 to 1000 growers per section but may be harvested by 3 to 10 contractors each. Transport from the transloading zones in each Inkanyezi section is provided by the haulier Unitrans. There are also

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8 other small grower areas as well as numerous individual small growers, usually in combinations with larger farms, for which transport is provided by various other hauliers as well as Unitrans. As in the case of the private commercial growers these growers use various different methods of harvesting and infield transport.

5.1.2 Millyard operations

When trucks arrive at the Sezela millyard, they firstly join one of three queues to gain access to the weighbridge, before being dispatched by the weighbridge to a specific offloading point. There is one queue for trucks containing bundled cane which allows these trucks access to the weighbridge as soon as it is available. Another queue is for Unitrans trucks and the third queue is for trucks from other hauliers and growers with their own transport. The Unitrans and other haulier trucks are allowed access to the weighbridge in a ratio dependent on the relative DRD's being supplied by Unitrans and the other hauliers. Thus, if Unitrans is supplying twice the DRD that the other hauliers are, two Unitrans trucks will be allowed in for every truck from another haulier.

There are four different offloading points in the millyard. If a truck contains bundled cane, it is routed directly to the bundle offloading point, where a gantry crane offloads the bundles either into a stockpile on the floor or, if there is space on the west table feeding cane into the mill, it offloads the bundles directly onto this table. The bundles are broken as they are offloaded onto the floor or table. If the truck contains loose cane, it is directed either to the east spiller, the west spiller or the dummy spiller where that cane is dumped onto the floor for storage in the ground stockpile. The east and west spillers dump the cane directly onto the tables feeding the east and west lines of the mill. The choice of which offloading point to send the truck to is determined by the number of trucks queued at each offloading point, this number being tracked at the weighbridge. There is a maximum number of trucks allowed at each offloading point and the order of priority is east, west, dummy. There is also a procedure whereby 30% of the loads entering the yard are tested for the sucrose content of the cane. The mill line on which testing is carried out is swopped every four hours from east to west and back again, so if a load is assigned to be tested, the truck is sent directly to whichever spiller is supplying the line that is being tested at that time.

There are two front end loaders fitted with grabs that clear cane from the dummy spiller area and transfer it to the main ground stockpile. These front end loaders can also feed cane into two shutes that supply the east and west lines of the mill respectively when there is no cane being fed from the spillers. For the west line, however, the priority after feeding from the spillers is to feed cane from the ground or broken bundle stockpiles onto the table using a gantry crane fitted with a large grab that can take loads of 7-8 tons. Currently there is one driver for both the large grab gantry and the bundle offloading gantry, so when bundles are being offloaded, the large grab gantry cannot operate and therefore loose cane may be fed via the west shute.

5.2 Conceptual Models

There are thus 85 farm combinations in the mill supply area that had to be modelled using different systems of both harvesting and transport. This implied that, for the harvesting and transport section, the level of detail at which the model was developed would have to be fairly coarse so that the model did not become too large, complex and slow running. In contrast, the millyard operations could be represented with greater detail, since the number of operations occurring in this area are limited and concentrated in one location.

5.2.1 Initial harvesting and transport model

The initial conceptual model was to represent the most common methods of harvesting and transport and then to weight the tonnage to be processed by each system according to the actual distribution of systems in the mill area or the distribution of systems that needed to be investigated. A flowchart of the initial harvesting and transport model structure is shown in Figure 4. The entities that flow through the model were taken to be individual tons of cane and the resources with which they interact were taken to be the equipment used in cutting, loading, offloading, and transport. These entities were given tags or attributes, such as the time at which they were burnt or cut so that the overall time in system or harvest-to-crush delay could be calculated when they reached the mill. Transport was modelled as an unlimited resource and travel times from the fields to the transloading zones and the transloading zones to the mill were sampled from triangular distributions. Variables were set up to track the tonnage of cane at various points in the system,

Figure 4. Flowchart of initial harvesting and transport model structure

33
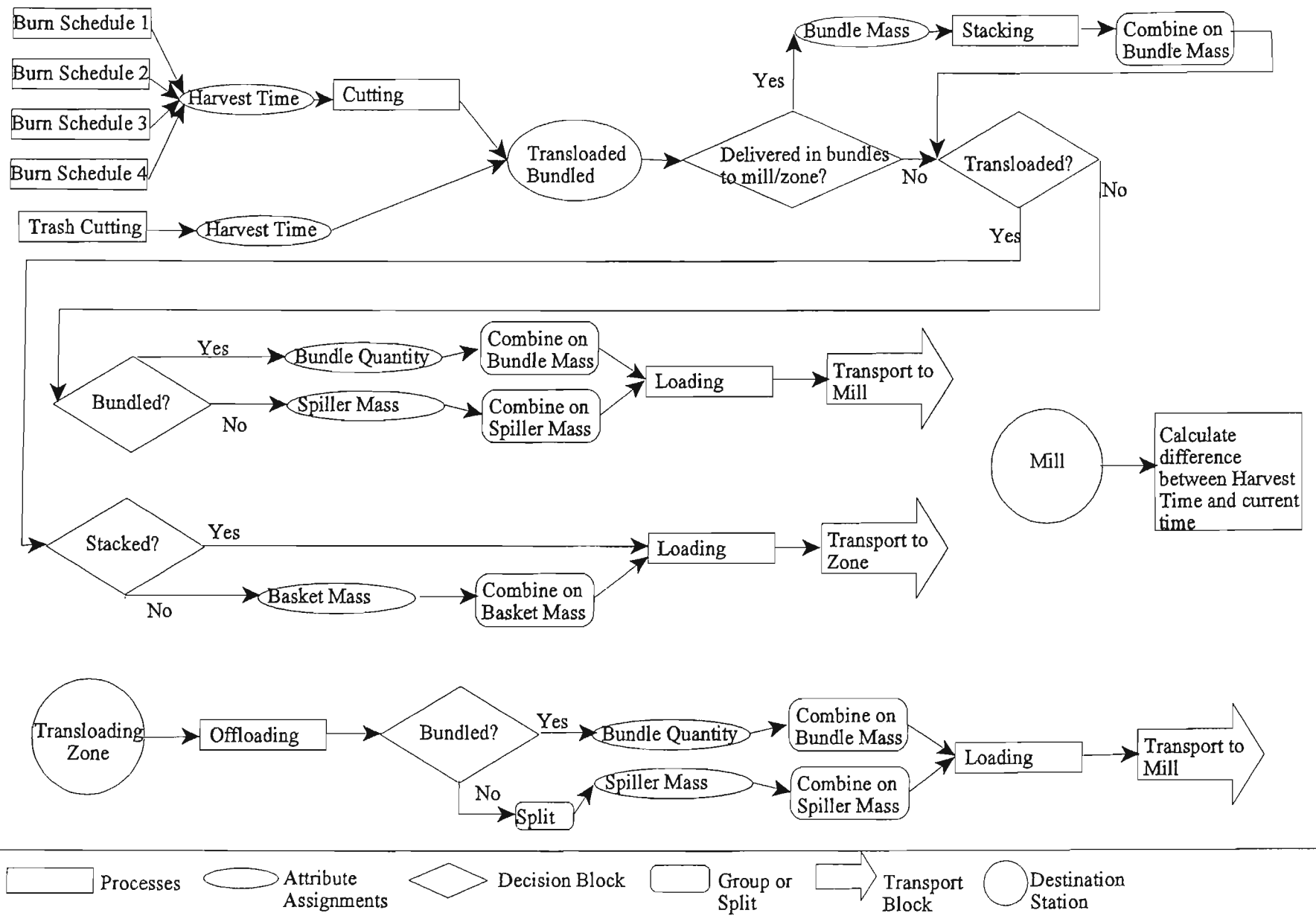
Figure 5. Flowchart of integrated model structure

35
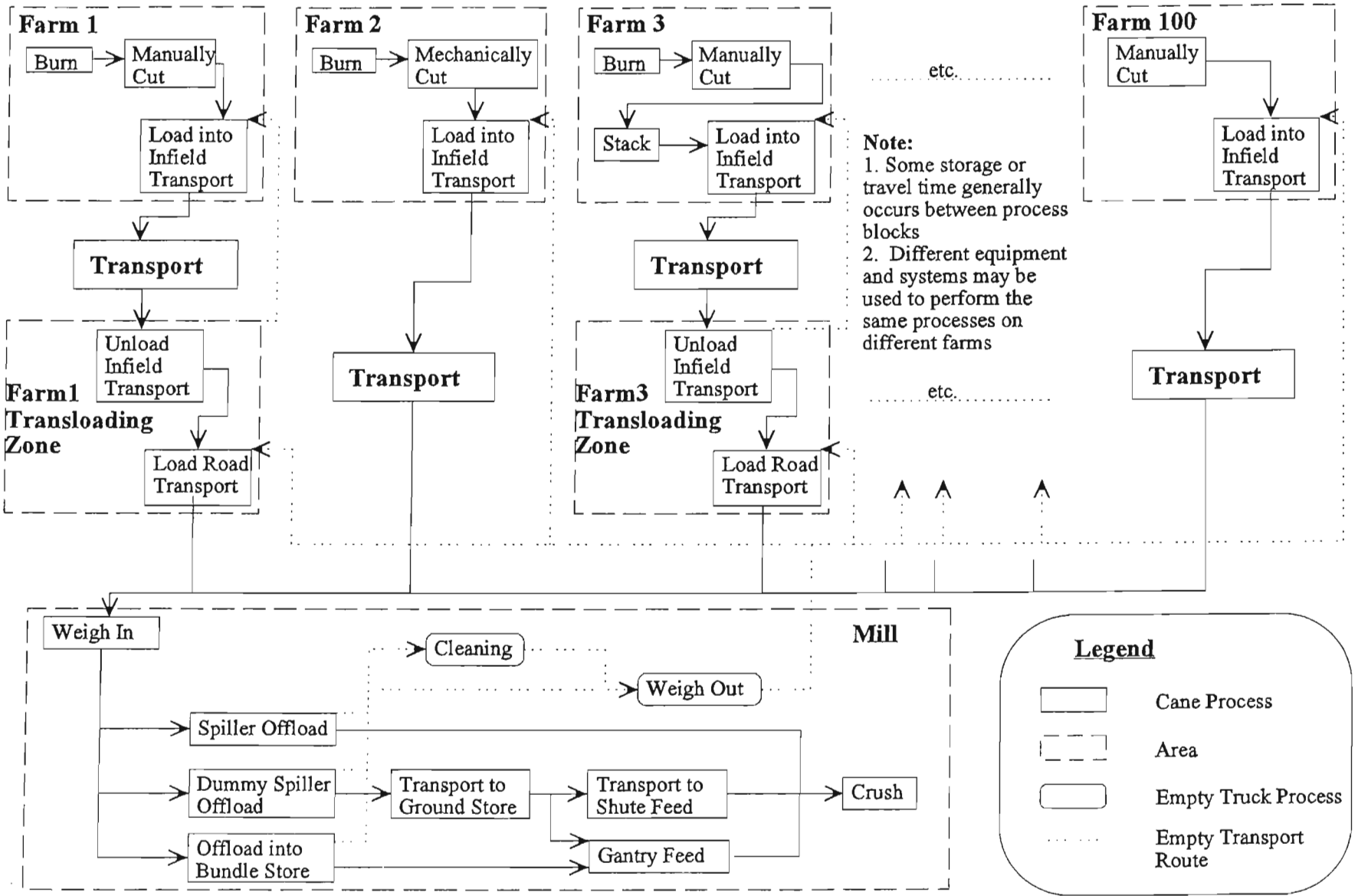
harvesting and transport logic relevant to the systems used on that particular farm. Thus the variable Transloads(30,1) would track the tonnage of cane in the transloading zone stockpile on the farm represented by the index 30. Similarly indexed variables would control which schedules for operations such as burning and transport were employed for each farm.

Furthermore, resources were set up for each farm to represent the equipment available for the harvesting, loading and reloading processes. Variables were also set up to represent the hauliers operating in the area. These variables kept track of the number of vehicles available and in use for each haulier as well as the location of the trucks in the system. A spreadsheet into which the initial values for the farm and haulier variables as well as the capacity of the resources could be entered and which was then read in by the model at the beginning of each run was developed to make the process of making changes to the structure of the modelled farms supplying cane to the mill easier and more user-friendly.

The millyard section of the model was adapted from the Arena model of the Sezela millyard developed by Simulation Services cc to investigate turnaround times of trucks offloading cane (Schaller, 1997). In the original model, the entities flowing through the system were truckloads of cane and therefore, in the adaptation of the model, the individual one ton entities of cane produced in the harvesting processes were batched into groups to represent the truckloads. These groups were broken up when the cane was offloaded onto the spiller tables or into the ground or bundle stockpiles. In this section of the model the resources with which the entities interact were the various millyard offloading facilities such as the weighbridge, the spillers and the gantry cranes. The model was further adapted to primarily record the time that the cane spent in the yard before being crushed rather than the turnaround time of the trucks in the yard. Turnaround time of the trucks in the yard was still indirectly modelled, since it impacted on how quickly vehicles could be available to remove cane from the transloading zone.

5.3 Integrated Model Structure

The model is divided into a number of sections, usually, but not always, where there is a change in location from one point to another such as when cane is moved from the field to the

transloading zone. The Arena flowcharts of the various processes involved in these sections are presented in Appendix B and described in the following discussion. Two further sections of the model are the experiment section where variables, schedules, resources and the like are defined along with the specifications of the model run length and starting condition, and the input spreadsheet from which data on the individual farms and hauliers as well as certain single input variables are read. A macro sets up the infield and transloading zone loading and offloading resources required for each farm. This macro, which is run by clicking on the 'SetupRes.exe' icon in the experiment section of the model, reads the capacity of the resources from the input spreadsheet and places the resource elements. The experiment section of the Arena model is illustrated in Figure B-1.

For reasons detailed previously, the basic time unit used in the model is an hour and the basic cycle of the system is a week since a week is the basis of most of the schedules employed in the sugarcane harvesting and delivery system. In the model, the day of the week, which affects various schedules, is tracked by a global variable called 'weekday' and whether it is day or night is tracked by another global variable called 'period'. The total number of days that has passed in the simulation is tracked by the global variable 'day'

5.3.1 Input spreadsheet

Portions of the 3 worksheets of the Excel spreadsheet are shown in Figure 6 and Figure 7. In the first worksheet, data for the schedules and systems used on the individual farms are entered. The combination numbers in the second column correspond to the index of the model variables into which the data are read. The second worksheet is a list of the hauliers operating in the area and the total number of vehicles each haulier uses. These hauliers are indexed for each grower in the first worksheet. If a grower performs his own transport, he indexes a separate haulier with a single vehicle. This worksheet also provides a summary of the DRD that each haulier has to transport in each of the twelve hour periods during the week. The third worksheet provides an overall summary of the tonnages on the various systems and schedules as well as a distribution of the planned deliveries to the mill through the week. This distribution is calculated from the tonnage provided by each farm and the schedules that each farm delivers on. The summary

Figure 6. Farm and haulier data spreadsheets

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Data Transfer Macro: Press Ctrl+r

Make sure that directory in data transfer macro is correct

Equipment numbers based on equations derived from survey data

0=24h, 1=day, 2=night

Combination Numbers Must Be Sequential   1=True, 0=False   Remember to alter the resource setup if these values are changed   1=Mon-Sat, 2=Tue-Su

Combination	Comb. No.	DRD	BurnSched	Bundled	Transloaded	SplitBundle	No. Infield Trailers	No. Zone Offloaders	No. Infield Loaders	No. Zone ReLoaders	Haulier No.	Delivery Period	Delivery Days	Distance
Arde Bros [P] L	1	151	1	0	1	1	2	1	2	1	1	1	2	33
Moodley KL	2	16	1	0	1	1	1	1	1	1	1	1	2	31
Clifton Park Es	3	129	2	0	1	1	2	1	2	2	2	0	2	31
Drumdarrock E	4	95	1	0	1	0	4	4	1	1	3	2	1	44
Cranbrook Far	5	59	3	0	1	0	1	1	1	1	5	1	1	46
Crookes PJ	6	74	2	1	1	0	2	2	2	2	6	1	1	48
Richards JF&D	7	104	1	0	1	1	2	1	2	1	7	2	1	36
Drummond AI	8	54	1	0	1	1	1	1	1	1	8	1	1	13
Drummond S [	9	35	1	0	1	1	1	1	1	1	8	1	1	15

Number	Hauler	No of Vehicles		Mon Day Deliveries	Mon Night Deliveries	Tue - Sat Day Deliveries	Tue - Sat Night Deliveries	Sun Day Deliveries	Sun Night Deliveries	9463	Max Loads per Truck per 12 hr Period
1	ARDE BR	3		30	0	197	0	166	0	1181	3
2	BLAMEY	1		0	0	64	64	64	64	774	3
3	C LEISEG	2		0	95	0	95	0	0	567	2
4	CHANDH	1		0	0	0	0	0	0	0	0
5	CRANBRO	1		59	0	59	0	0	0	357	3
6	CROOKES	1		74	0	74	0	0	0	443	3
7	DOVEA	1		0	104	0	104	0	0	623	4
8	DUMEZWE	3		253	229	253	229	0	0	2892	3
9	DUNGAY T	1		0	0	0	0	0	0	0	0
10	ELLINGHA	4		219	219	219	219	0	0	2626	2

Summary Stats		1
	DRD Tonnage	Weeks Tonnage
Total DRD	10559	63355
Bundled	682.855	4097
Transloaded	10559.115	63355
SplitBundle	6429.1875	38575
DRD Stacked	7112.0425	42672
BurnSched1	4535.31	27212
BurnSched2	4104.6025	24628
BurnSched3	1287.4623	7725
BurnSched4	37.635	226
BurnSched1n	399	2396
BurnSched2n	195	1169
BurnSched3n	0	0
BurnSched4n	0	0
TrashCut	0	0
		63355
Prob1		277
Day	5770	
Night	4789	63355
Mon Deliveries	7169	
Tues - Sat Deliveries	10347	
Sun Deliveries	4450	63355
Mon Day Deliveries	5063	
Mon Night Deliveries	2106	
Tues - Sat Day Deliverie	5664	
Tues - Sat Night Deliveri	4683	
Sun Day Deliveries	1237	
Sun Night Deliveries	3213	63355
DRD Check	OK	
DelivPeriodChecks	OK	
TrailerChecks	OK	
SplitChecks	OK	
BurnChecks	OK	

Single Input Variables	
No of Vehicles	110
No of Farms	85
No of Hauliers	34
Haulier Ratio	0.522
LoadedSpeed (km/h)	35
UnLoadedSpeed (km/h)	45
InfieldLoaderRate (tons/	22
ZoneLoaderRate (tons/h	35
Bundle Load T min	0.06777
Bundle Load T mode	0.08333
Bundle Load T max	0.1
WeeklyTarget (tons)	67000
InitialGroundStock (tons)	0
InitialBunStore (tons)	0
StatFarmNo1	44
StatFarmNo2	48
AnimFarm1	1
AnimFarm2	2
AnimFarm3	3
AnimFarm4	4

Delivery Plan	Tonnage	% Weekly Tonnage
Mon	5063	7.99
	2106	3.32
Tues	5664	8.94
	4683	7.39
Wed	5664	8.94
	4683	7.39
Thurs	5664	8.94
	4683	7.39
Fri	5664	8.94
	4683	7.39
Sat	5664	8.94
	4683	7.39
Sun	1237	1.95
	3213	5.07
	63355	100

Planned Deliveries to Mill

(Bar chart: % Weekly Tonnage vs Day and Period — Mon, Tues, Wed, Thurs, Fri, Sat, Sun)
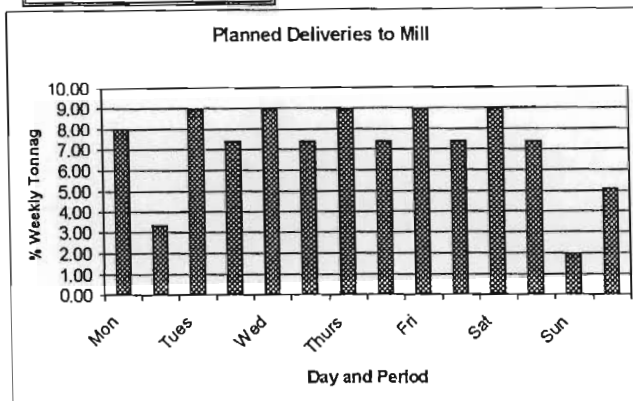
Figure 7.   Summary spreadsheet

worksheet also allows for variables applicable to the whole model, such as loader rates and truck speeds, to be entered. The individual farms which the user may want to animate and collect statistics on can also be specified here.

In the first worksheet, 'BurnSched' references one of the 9 schedules of burning set up in the model. Burning is assumed to start at 06h00 and a maximum 3 hour slot is allowed for the operation to be completed. With burn schedule 1, burning is performed on a daily basis from Monday to Saturday. With burn schedule 2, burning is performed Monday, Wednesday and Friday. On burn schedule 3, burning is performed on a Monday and a Thursday and on burn schedule 4 burning is only performed on a Monday morning. On burn schedule 5, burning is not

performed at all - the cane is trashcut or cut green. Burn schedules 6 to 9 correspond to schedules 1 to 4, but the burning is performed at 18h00 instead of in the morning. 'Bundled', 'Transloaded' and 'SplitBundle' are a 0-1 variables. 'Bundled' specifies whether or not the cane from a particular farm is delivered to the mill in bundle form, 'Transloaded' whether it is transloaded or not and 'SplitBundle' whether bundles formed in the fields are broken in the zone or not. The number of infield trailers, infield loaders, zone offloaders and zone reloaders represent the capacity of resources available on each farm for transport and infield operations. Infield loaders can be self-loading trailer or bell loaders - if they are self-loading trailers, the number merely is equal to the number of infield loaders. The situation is similar for self-offloading trailer and the zone offloaders. Zone reloaders can be bell loaders or cranes since the appropriate loading rate is automatically used in the model. 'Haulier No.' indexes the hauliers listed in the second worksheet. If the delivery period number is 0, the farm delivers to the mill 24 hours a day, if it is 1, the farm delivers day shift (06h00 to 18h00) only and if it is 2, night shift only (18h00 to 06h00). If the delivery days number is 1, the farm delivers to the mill Monday to Saturday, if it is 2, Tuesday to Sunday and if it is 3, Monday to Sunday.

An Excel macro, which is activated in the spreadsheet by pressing 'control' and 'r', copies the values in the spreadsheets (not including the resource capacity values transferred by the 'SetupRes.exe' macro) that are required by the model into 'wks' format which the Arena model can then read. This data is read in by the model at the beginning of each run.

5.3.2 Burning and trashcutting processes

The burning and trashcutting processes are illustrated in Figure B-2. At the beginning of each day in the simulation an entity is created for each farm and assigned an attribute which will be its farm number. This farm number is used to index the variables specifying such data as the DRD that the farm has to produce and the systems and schedules that the farm operates on. Each entity is also assigned a burning delay which is sampled from a triangular distribution with a minimum of 0.333 hours, mode of 1 hour and maximum of 3 hours. Sampling from this distribution simulates the variable amount of time that the burning process may take.

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If the weekday is correct for the burn schedule that the farm is operating on, each entity is sent to a process block that operates on the appropriate schedule or otherwise it is disposed. The process blocks have a very large capacity so that each farm effectively gets its own burning process. The process time for each entity is calculated by dividing the burn time sampled from the triangular distribution by the DRD each farm has to provide for that day. If the schedule is not a daily burn schedule, the DRD used is multiplied by 2, 3 or 6 for the three times a week, twice a week and once a week burn schedules respectively, so that the correct tonnage is produced. After the process block, each entity is duplicated if the time since burning started is less than the burn time sampled for that farm. The duplicate entity is sent back to the process block and the original carries on to the cutting process. After the burn time is over, duplicate entities will not be sent back to the process block and thus, due to the manner in which the process times were calculated and the fact that each entity represents 1 ton of cane, the required DRD will have been produced. The process of producing trashcut cane is identical to that of producing burnt cane except that the entities are produced over the period of the cutting/stacking time which is assumed to be 10 hours per day (06h00 to 16h00) instead of the burn time and the cane does not have to go to the cutting process afterwards.

After burning or trashcutting, each entity is assigned a Harvest Time attribute which records the current time so that the time since harvesting can be calculated at later stages in the model and then the entity is added to the 'BurntCut' stockpile for its particular farm . The cutting of burnt cane process is next and here, the process time is calculated by dividing the cutting/stacking time by the farm's DRD so that one DRD should be cut each day, Monday to Saturday. This emulates the manner in which a grower will adjust the number of labourers involved in cutting to suit his DRD. Cutting is assumed to start at 06h00 and therefore, cane burnt in the evening will only start to be cut the following morning. Overlap burning, or burning new cane before all the previously burnt cane has been cut, is not allowed for. The cut entities are then removed from the BurntCut stockpiles and routed to the stacking process with a zero routing time, since there is no actual transport involved.

5.3.3 Stacking process

The stacking process is illustrated in Figure B-3. If the cane is to be stacked, i.e. if the variables Bundled or SplitBundle for the particular farm equal 1, the cane is added to the 'CutStack' stockpile before entering the stacking process. Otherwise the cane is added to the 'CutLoad' stockpile and goes directly to the loading process.

The one ton entities entering the stacking process are firstly batched into groups of 3 to 7 to represent stacks of 3 to 7 tons. If the cane is to be delivered to the mill in bundle form, the size of the batch to be formed is sampled from a triangular distribution with minimum 3, mode 4 and maximum 5 tons which is then rounded to the nearest integer. If the bundles are to be broken up in the transloading zones, the distribution has minimum 3.5, mode 6 and maximum 6.5 tons. These distributions are resampled for each farm after each stack is produced. The process time for stacking is calculated in the same way as that for cutting, except that the per ton time is multiplied by the tonnage in each stack to obtain a time for the stack entity to be processed. After the stacking process the CutStack stockpile is decremented by the tonnage of the stack entity and the entity is added to the 'StackLoad' stockpile for the particular farm before going to the loading process.

5.3.4 Loading processes

The four types of loading processes modelled are illustrated in Figure B-4. If the cane is to be delivered directly to the mill in bundle form, the bundles are combined into truckloads of 6 to 9 stacks. If the cane is to be delivered directly to the mill in loose form, the individual one ton entities are combined into spiller loads of 24 to 35 tons. If the cane is to be transloaded and was stacked, individual stacks are loaded onto tractor-trailer units for transport to the zone. If the cane is to be transloaded and has not been stacked, the individual one ton entities are combined into bin or basket trailer loads of 3 to 8 tons. The sizes of the bundle and spiller truckloads and the basket trailer loads are sampled and resampled in a similar manner to that in which the sizes of the bundles in the stacking process were determined, except that for the bundle truckloads, the distribution is uniform with minimum 6 and maximum 9 bundles, for the spiller truckloads it is

triangular with minimum 24, mode 28 and maximum 35 tons and for the basket trailer loads it is triangular with minimum 3.5, mode 7 and maximum 7.5 tons.

The loading process cannot occur if transport is not available to load the cane into and therefore, a loop checks if there is a vehicle available in the field before allowing the loading process to begin. If there is no vehicle available a delay of 1 minute occurs before the check is performed again. Similarly, loading cannot occur if there is no loader resource capacity available. With self-loading trailers the loader resource capacity (as specified in the farm data section of the input spreadsheet) is always equal to the number of trailers, so this situation will never occur, but if the trailers are being loaded by a loader such as a Bell, they may have to wait until a loader is finished loading another trailer.

If bundles are being loaded, the loading process time is calculated by multiplying the time to load a bundle by the number of bundles to be loaded, whereas if loose cane is being loaded, the tonnage to be loaded is divided by the infield tons per hour loader rate. For the bundle loading time, a minimum mode and maximum for a triangular distribution are specified in the input spreadsheet and this distribution is sampled each time a bundle loading time is required. An average infield loader rate is specified in the input spreadsheet.

After loading, the CutLoad or StackLoad stockpiles for each farm are decremented by the tonnage of each load and the loads are routed to the mill or transloading zones. If the destination is the transloading zone, the trip time is sampled from a triangular distribution with minimum 6 minutes, mode 12 minutes and maximum 18 minutes. If the destination is the mill the trip time is calculated by dividing the distance of the farm from the mill, which was specified in the farm data section of the input spreadsheet, by the truck loaded speed which was specified in the summary section of the spreadsheet. Variables tracking the total amount of cane being transported from the fields to mill and fields to zones are also incremented by the tonnage of the loads at this point.

5.3.5 Transloading processes

The transloading processes are illustrated in Figure B-5. Tractor-trailer loads entering the transloading zones firstly go through an offloading process. If the trailer is self-offloading, this process can always occur immediately since the capacity of the offloader resource will be equal to the total number of trailers, but if the tailer is being offloaded by crane it may have to wait until there is offloader capacity available. The process time for offloading of both loose and stacked cane is assumed to be the same as the time to load a single stack. At this point a duplicate entity is routed back to the fields to make the tractor-trailer unit available in the field again. The trip time is sampled from the same distribution as for the field-to-zone trip. After the duplicate entity reaches the field and increases the number of tractor-trailer units available, it is disposed. At this point too, the variable tracking the total amount of cane in transport from field to zone is decremented by the tonnage of the load and the load is added to the 'Transloads' stockpile for the particular farm.

The load entities are then split into their original one ton entities. If the cane is to be delivered to the mill in spiller form, the one ton entities are grouped into loads in the same manner as that in which the spiller loads to be transported directly to the mill were formed in the fields. If the cane is to be delivered to the mill in bundle form, the batches are reformed immediately, and then 6 to 9 bundles are combined to form a truckload. The sizes of the spiller loads and the number of bundles or stacks in a bundle load are sampled from a triangular distribution with minimum 24, mode 28 and maximum 35 tons, and a uniform distribution with minimum 6 and maximum 9, respectively. The values obtained are rounded off to the nearest integer and the distributions are resampled for each farm after each load is formed.

Once it has been ascertained that there is transport present and reloading capacity is available as was done in the infield loading processes, the zone loading process can occur. The process time for the loading of spiller trucks is calculated using the tonnage of the load to be formed and a tons per hour rate for a loader working in transloading zone conditions which can be specified in the summary sections of the input spreadsheet. The process time for loading of a bundle truck is once

again calculated by multiplying the time to load a bundle by the number of bundles in the load. The Transloads stockpile for each farm is decremented and the variable tracking the total amount of cane in transport from the zones to the mill is incremented by the tonnage of the loads at this point. The loads are then routed to the mill with a trip time based on the distance of the particular farm from the mill and the truck loaded speed.

5.3.6 Vehicle availability logic

Since most farms use a haulier to transport cane from the field or zone, some control of where and when trucks are dispatched was necessary in the model. The logic of this control, which is based on the calculated tonnage that needs to be transported from each farm on a particular day, is illustrated in Figure B-6. Thus a logic entity is created for each farm that assigns the tonnage to be transported at the beginning of each 12-hour period. The logic entity first checks that the current period (day or night) corresponds to the delivery period for the particular farm. If it does not, then the tonnage to transport is assigned to zero and the entity is delayed for 12 hours before checking the logic again.

If the periods correspond, then the entity compares the current weekday and the delivery schedule (delivery days) for the farm. If the delivery day specified for the particular farm in the input spreadsheet implies that no cane is to be delivered on a particular day, then the tonnage to transport for that farm on that day is set to zero. Otherwise, if the farm delivers cane to the mill Monday to Saturday and the current period is day, then the tonnnage to transport is set according to the following equation:

$$TtT = S + \frac{DRD}{2 - (DvP \neq 0)} \tag{1}$$

Where: TtT =   tonnage to transport

              S   =   tonnage left in the field or transloading zone stockpile (depending on whether the farm practises transloading or not) from previous days deliveries.

              DRD =   daily required delivery for particular farm (tons)

              DvP =   delivery period for particular farm

Thus, if the farm is on a 24 hour delivery plan (DvP=0), half the DRD should be left in the stockpile at the end of the day to be transported at night.

If the farm delivers Tuesday to Sunday 24 hour or day only and the current period is day, then the tonnage to transport is determined by applying Equation 2.

$$\text{TtT} = \text{S} - \frac{\text{DRD}}{2} * (\text{DvP} = 0) \tag{2}$$

Where the variables are defined as for Equation 1. The rationale for this equation is that on Tuesday there is one day's DRD in the stockpiles from harvesting performed on the Monday and so on for the rest of the week and if the farm is on a 24 hour delivery plan, then half the DRD should once again be left in the stockpile at the end of the day to be transported at night.

If the farm delivers seven days a week, 24 hour or day only and the current period is day, then the tonnage to transport is calculated from the following equation:

$$TtT = S + \left(\frac{\frac{6}{7}DRD}{2 - (DvP \neq 0)} - \frac{Wd-1}{7} * DRD \right) * (Wd \neq 7)$$

$$- \frac{\frac{6}{7}DRD}{2} * (DvP = 0) * (Wd = 7) \tag{3}$$

Where: Wd   =   Weekday (Monday = 1, Sunday = 7)

and the other variables are defined as for Equation 1

This equation assumes that DRDs are based on 6 days a week deliveries and therefore farms delivering 7 days a week will deliver 6/7ths of their DRD each day. For Mondays to Sundays ($Wd \neq 7$), the tonnage to transport is the tonnage in the stockpile added to the tonnage to be delivered that day. If the farm is on 24 hour deliveries then only half the tonnage to be delivered for that day is added. Furthermore, each day an extra 1/7th of the DRD is left in the stockpile to be delivered on a Sunday. On Sundays, the tonnage to transport is whatever is in the stockpile less half the tonnage to be delivered that day if the farm is on 24 hour deliveries.

If the farm is assigned to delivery during the night period or 24 hours and the current period is night then the following rules apply. If the farm delivers Monday to Saturday, then the tonnage to transport is set to the tonnage left in the field or transloading zone stockpile. If the farm delivers Tuesday to Sunday, then the tonnage to transport is set to the tonnage left in the field or transloading zone stockpile less 1 day's DRD unless the weekday is Sunday. If the farm delivers to the mill seven days a week then the tonnage to transport is calculated from the following equation:

$$TtT = S - \frac{Wd}{7} * DRD * (Wd \neq 7) \qquad (4)$$

Where all variables are as defined in Equations 1 and 3. This equation is used for the same reasons as the equation for day period deliveries. The $(Wd \neq 7)$ term in the equation ensures that, on a Sunday, the tonnage to transport is only the tonnage in the stockpile since no cane is harvested on a Sunday.

Another logic entity is created for each farm that actually performs the dispatching of trucks to the farms if required. This entity checks if the tonnage to transport from that farm is greater than or equal to 35 tons and if the haulier that the farm employs has at least one vehicle not in use. If the tonnage to transport is zero, i.e. the weekday does not correspond to one of the farm's delivery days or the current period does not correspond to the farm's delivery period, then the entity is delayed until the start of the next day when the checks are performed again. If both these checks prove false, then the entity is delayed for one minute before the checks are performed again. If, however, the first check proves true, then the tonnage to transport for the farm is decremented by 29 tons (which is the average mass of the loads) and the number of vehicles that the concerned haulier has available is decremented by one.

A duplicate entity is then created which is routed to the farm fields or transloading zone (depending on whether or not the farm practises transloading) with a trip time calculated from the distance of the farm from the mill and the unloaded speed for road vehicles that was specified in the summary section of the input spreadsheet. The original entity is delayed for three quarters of an hour before all the checks are performed again.

Entities from the dispatching logic arriving at the farm fields or transloading zones, increase the number of trucks present on the farm so that loading can occur if there is loading resource capacity available and sufficient tonnage to form a truck load. These entities are then disposed.

5.3.7 Millgate processes

The millgate processes are illustrated in Figure B-7. Load entities arriving at the mill are firstly assigned an attribute which will determine whether or not the load is to be tested for sucrose content. This attribute is assigned with a 30% chance. The entities then enter one of three queues. The first queue, which is for bundled load entities, has a priority of 1 for the weighbridge resource. The other two queues, which are for loose cane loads transported either by Unitrans or another haulier, have a priority of 2 or 3. The priority of the Unitrans queue for each load is sampled from a discrete distribution which is based on the ratio between the DRDs transported by the two groups, and the priority of the other queue is then assigned accordingly. The entity in the queue with the lowest priority is allowed onto the weighbridge first.

Once on the weighbridge the entity is delayed for the weighing in time which is sampled from a triangular distribution with minimum 1.5 minutes, mode 2.34 minutes and maximum 3 minutes. The entity is then assigned an offloading destination as described in the Millyard Operations section, or if the offloading points are all full, the entity is delayed for a minute before the model attempts to assign a destination again. The entity then moves off the weighbridge so that other loads can move on and is routed to an interim point in the millyard with a trip time sampled from a triangular distribution with minimum 2 minutes, mode 3 minutes and maximum 4 minutes. At the interim point the entities are routed to their assigned destinations with a trip time sampled from a triangular distribution with minimum 0.75 minutes, mode 0.92 minutes and maximum 1.08 minutes if the destination is the east or west spillers, minimum 0.42 minutes, mode 0.5 minutes and maximum 0.58 minutes if the destination is the dummy spiller and minimum 0.5 minutes, mode 0.58 minutes and maximum 0.75 minutes if the destination is the bundle offloading point.

5.3.8 Spiller offloading

Load entities arriving at the various spillers firstly attempt to seize the spiller resource as is illustrated in Figure B-8. If they are unable to do so, they queue until the spiller becomes available. Once they are allowed onto the spiller they delay for the time taken to hook up the trailers' spiller bar. This time is sampled from a triangular distribution with minimum 0.17 minutes, mode 0.38 minutes and maximum 0.75 minutes. A check is then performed to determine if the tonnage currently on the table or in the dummy spiller area added to half the mass of the load to be spilt (since it is assumed that all the spiller trucks have double trailers) will be less than the maximum tonnage allowed on the table at one time. For the east table, this maximum is 55 tons, for the west table it is 78 tons and for the dummy spiller area it is taken to be 36 tons. If this condition is not true, then the entity is delayed until the condition does become true. The entity is then delayed for the spill time which is sampled from a triangular distribution with minimum 0.38 minutes, mode 0.66 minutes and maximum 1.08 minutes. The tonnage of cane on the table or in the dummy spiller area is then incremented by half the mass of the load being spilt and for the dummy spiller, half the one ton entities making up the load are routed to the dummy spiller area with a zero trip time.

The feeding of cane into the mill from the east and west tables is modelled by treating the tonnage on each of the tables as a continuously changing variable. The rates of change of the variables are controlled by rates that can be altered in the model. The crush plan, which specifies that 12% of the target tonnage to be crushed is crushed on a Monday, 15% is crushed Tuesday to Saturday and 13% is crushed on a Sunday, is used to calculate the rate at which cane is fed into the mill. The target tonnage to be crushed can be specified in the summary section of the input spreadsheet and each of the tables provides half of the tonnage that the mill crushes. If the tonnage on a table becomes zero, an entity is created that assigns the rate of change of tonnage on that table to zero until the tonnage on the table becomes greater than 8 tons, when the rate of change is reassigned to its correct value according to the crush plan.

After the first halves of the loads have been spilt, the load entities are delayed for the time taken to unhook the spiller bar, which is sampled from a triangular distribution with minimum 0.6

minutes, mode 0.75 minutes and maximum 0.92 minutes. They are then delayed for the time taken for the truck to move up so that the second trailer is adjacent to the spiller, which is sampled from a triangular distribution with minimum 0.18 minutes, mode 0.35 minutes and maximum 0.52 minutes. Thereafter the process of hooking up, checking the tonnage on the table, spilling and unhooking is repeated for the second trailer before the spiller resources are released so that the next trucks in the queues can be unloaded if they have arrived.

For the east and west spillers, the load entities are disposed of after the average time that the original one ton entities making up the load have spent in the system has been recorded. The load entities from both the east and west spillers and the dummy spiller, which now represent the empty trucks, are then sent either to the cleaning station or to the out going weighbridge. 60% of the empty trucks are sent to the cleaning station. The route time from any of the stations to the out going weighbridge is taken as 0.5 minutes. The route time from the east spiller to the cleaning station is sampled from a triangular distribution with minimum 0.92 minutes, mode 1.0 minutes and maximum 1.08 minutes and the route time from the west and dummy spillers to the cleaning station is sampled from a triangular distribution with minimum 1.17 minutes, mode 1.5 minutes and maximum 2.0 minutes.

5.3.9 Bundle offloading, storage and feeding of bundle stockpiled cane

The bundle offloading and storage logic is illustrated in Figure B-9. Load entities arriving at the bundle offloading point first of all have to ensure that the large-grab gantry-crane is available before they can seize the bundle-offloading gantry-crane resource, since there is only one driver for both of these cranes and so, effectively, both of the cranes have to be available before either one can operate.

If the west spiller is not currently in use and the amount of cane on the west table is less than 15 tons, then the west spiller resource is seized so that no trucks can start unloading onto the west table and the load entity is delayed for the time taken to offload the bundles directly onto the west table. This time is calculated with the following equation:

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$$Time = (\frac{Number\ of\ Bundles}{2} + 1) * Bundle\ Gantry\ Feed\ Time \qquad (5)$$

The *bundle gantry feed time* is sampled from a normal distribution with mean 3 minutes and standard deviation 5 minutes. The tonnage on the west table is then incremented by the mass of the load and the variables tracking the total amount of cane in road transport are decremented by the mass of the load. The west spiller and bundle gantry resources are subsequently released and the large-grab gantry transporter is freed. A duplicate of the load entity is routed to the outgoing weighbridge with a trip time sampled from a normal distribution with a mean of 1 minute and standard deviation of 0.1 minute. The load is then split into its original one ton entities before the times that the entities have spent in the system are recorded and the entities are disposed.

If, however, the west table was in use or the amount of cane on the table was greater than 15 tons when the bundle-offloading gantry resource was seized, then the load entity is delayed for the time taken to offload the bundles onto the ground. This time is calculated with the following equation:

$$Time = (Number\ of\ Bundles + 1) * Bundle\ Gantry\ Offload\ Time \qquad (6)$$

The *bundle gantry offload time* is sampled from a triangular distribution with minimum 2 minutes, mode 2.5 minutes and maximum 3 minutes. The bundle gantry resource is then released, the large-grab gantry transporter is freed and the tonnage in the bundle stockpile is incremented by the mass of the load. Thereafter, the procedure is the same as that for the bundles offloaded directly onto the west table except that, instead of being disposed after the load has been split into its original one ton entities, the entities are stored until they can be fed into the mill by the large-grab gantry-crane.

A logic entity created at the beginning of the simulation checks if the tonnage in the bundle stockpile is greater than 600 tons and if it is, checks if there is sufficient space on the west table to take a further 8 tons of cane, before a global variable describing the mass of a large-grab gantry crane load is assigned and a signal for cane to be fed onto the table from the bundle stockpile is sent. If there is not more than 600 tons of cane in the bundle stockpile, the logic entity checks that there is more than 10 tons in the bundle stockpile, that the west spiller is not in use

and that the tonnage on the west table is less than 15 tons, before immediately assigning the global variable and sending the signal as previously. The logic entity is then disposed if either of these options is taken. If neither of these options are true, then the logic entity is delayed for the stock check time before testing the logic again.

One ton entities of cane waiting in the bundle stockpile that receive the release signal are batched into groups according to the global mass variable assigned in the bundle stockpile feed logic loop. The load entity then requests the gantry crane transporter and when it is available, the bundle stockpile is decremented by the mass of the load . At this point, a duplicate entity is sent to the bundle stockpile feed logic loop to check the logic again. The grab pick up and drop off times are included in the transport time from the bundle stockpile to the west table. This time is calculated according to the gantry crane speed which is sampled from a triangular distribution with minimum 6.2 km/h, mode 8.2 km/h and maximum 9.3 km/h and the distance between the two stations which is set at 50m. All load entities arriving at the west table grab drop-off point immediately free the gantry crane transporter before incrementing the tonnage on the table by the mass of the load. The load entities are then split into their original one ton entities before the time that each entity has spent in the system is tallied and the entities are disposed.

5.3.10 Dummy spiller area clearing

The one ton entities of cane arriving in the dummy spiller area from the dummy spiller, as illustrated in Figure B-10, are firstly assigned an attribute describing the mass of the front-end loader grab load in which they are to be transferred from the dummy spiller area to the main ground stockpile. This mass has an equal chance of being three or four tons and the entities are then batched into groups based on these attributes. Each load entity subsequently requests one of the two front-end loader transporter units and when it has gained control of one is delayed for the grab load time which is sampled from a triangular distribution with minimum 0.1 minutes, mode 0.2 minutes and maximum 0.25 minutes. The tonnage in the dummy spiller area is then decremented by the mass of the load and the front-end loader transports its load to the main ground stockpile. The trip time for this transport operation is calculated from the speed at which

the transporter moves which is taken to be 6.72 km/h and the distance between the two stations which is set at 50m.

When the front-end loader arrives at the ground stockpile, the load entity is delayed for an offloading time which is sampled from a triangular distribution with minimum 0.25 minutes, mode 0.5 minutes and maximum 0.65 minutes, before the front-end loader transporter is freed to go and get another load and the tonnage in the ground stockpile is incremented by the mass of the load. The load entity is then routed to a secondary ground station with a zero trip time where it is split into its original one ton entities and waits for a signal indicating that the mill needs to be fed from the ground stockpile.

5.3.11 Feeding of ground stockpiled cane

The logic controlling the feeding of ground stockpiled cane is illustrated in Figure B-11. At the beginning of the simulation, four logic entities are created that monitor if the mill needs to be fed from the ground stockpile. These logic entities first check that the east spiller is not in use, the tonnage on the east table is less than 15 tons and there is more than 10 tons in the ground stockpile. If all of these are true then the global destination variable is assigned the value one and the global variable describing the mass of a front-end loader grab load is assigned before the release signal is sent and the logic entity that took the branch is disposed

If this first test did not evaluate as true, then the logic entities check if the west spiller is not in use, the tonnage on the west table is less than 15 tons and there is more than 10 tons in the ground stockpile. If all of these are true then the global destination variable is assigned the value two. The logic entity then checks if the large-grab gantry-crane is in use and if it is, the global variable describing the mass of a front-end loader grab load is assigned before the release signal is sent and the logic entity is disposed as previously. However, if the large-grab gantry-crane is not in use, the global variable describing the mass of a large-grab gantry-crane load is assigned. This mass is determined by rounding off to the nearest integer a value sampled from a triangular distribution with minimum 7, mode 8 and maximum 9 tons. The release signal is then sent and the logic entity is disposed as before.

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If neither of the first two options are true, and the tonnage in the ground stockpile is greater than 3000 tons, then the global destination variable is assigned the value zero. This means that cane will be fed into whichever table is not being tested for sucrose content at that time. If this table is the east table, the entity is then delayed until the east table has sufficient space available to take a further 4 tons of cane. A global variable describing the mass of a front-end loader grab load is then assigned as previously and a signal is sent to release the appropriate number of entities from the ground stockpile. The logic entity is then disposed. If the table not being tested is the west table, the logic entity is delayed until the west table has sufficient space available to take a further 8 tons of cane before it enters the logic described in the second option above just after the global destination variable has been assigned.

If none of the above three options are true then the logic entity is delayed for the stock check time before the options are tested again.

One ton entities of cane waiting in the ground stockpile that receive the release signal are batched into groups according to the global mass variable assigned in the loose cane feed logic loop. These load entities are then assigned a destination attribute according to the global destination variable.

If the load is to be transported by front end loader, one of the front-end loader transporter units is requested and when one is available, the load entity is delayed for the grab load time which is sampled as before. The ground stockpile is then decremented by the mass of the load and a duplicate entity is sent to the loose cane feed logic loop to restart the logic. The load entity is then transported to the appropriate shute according to the destination attribute. The trip time is calculated as previously except that the distance between the main ground stockpile and the shutes is 80m.

If the load is to be transported by the large-grab gantry-crane, the gantry-crane transporter is requested and when it is available, the ground stockpile is decremented by the mass of the load before a duplicate entity is sent to the loose cane feed logic loop as before. The grab pick up time is included in the transport time from the main stockpile to the west table. This time is calculated

according to the gantry crane speed which is sampled from a triangular distribution with minimum 6.2 km/h, mode 8.2 km/h and maximum 9.3 km/h and the distance between the two stations which is set at 100m.

Load entities arriving at the shutes, firstly seize the particular shute resource and once a shute resource becomes available, delay for a shute feed time which is sampled from a triangular distribution with minimum 0.1 minutes, mode 0.2 minutes and maximum 0.25 minutes. The shute resource is then released, the front-end loader transporter is freed to go and get another load and the tonnage on the particular table is incremented by the mass of the load. Since the grab drop time is also included in the gantry crane transport time, all load entities arriving at the west table grab drop-off point immediately free the gantry crane transporter before incrementing the tonnage on the table by the mass of the load. The load entities are then split into their original one ton entities before the time that each entity has spent in the system is tallied and the entities are disposed.

5.3.12 Cleaning and weighing out processes

Entities representing empty trucks arriving at the cleaning station illustrated in Figure B-12, are delayed for the cleaning time which is sampled from a triangular distribution with minimum 5 minutes, mode 11.85 minutes and maximum 17.55 minutes. They are then routed to the out going weighbridge with a route time sampled from a normal distribution with mean 1.75 minutes and standard deviation 0.25 minutes.

Empty truck entities arriving at the outgoing weighbridge station firstly have to seize the outgoing weighbridge resource and when this resource becomes available, are delayed for the weigh-out time which is sampled from a triangular distribution with minimum 1.28 minutes, mode 1.95 minutes and maximum 2.55 minutes. The outgoing weighbridge resource is then released before the time that the trucks have spent at the mill and in the yard is tallied and the number of available vehicles for the particular hauliers is increased. The empty truck entities are then disposed.

5.4 Integrated Model Animation

Four farms are represented in the harvesting and transport section of the animation which is illustrated in Figure 8. The particular four farms to be represented can be altered in the summary section of the input spreadsheet. When the model is started with the animation set to be executed, a macro brings up a dialogue box that asks if the user wants to change the animated farms. If the animation farms have been changed in the spreadsheet (and the data transfer macro has been executed) then the user should click yes and the program will alter all the animation constructs appropriately.

The blue variable boxes show the level of the various stockpiles on each farm. The BurntCut stockpile represents cane that has been burnt and is waiting to be cut. The CutStack stockpiles represent cane that has been cut and is waiting to be stacked. The StackLoad stockpiles represent cane that has been stacked and is waiting to be loaded. The CutLoad stockpiles represent cane that has been cut and not stacked (windrowed) and is waiting to be loaded. The Transloads stockpiles represent cane on the transloading zone. Only the representative stockpiles applicable to the harvesting and transport systems used on the farm being animated will be used.
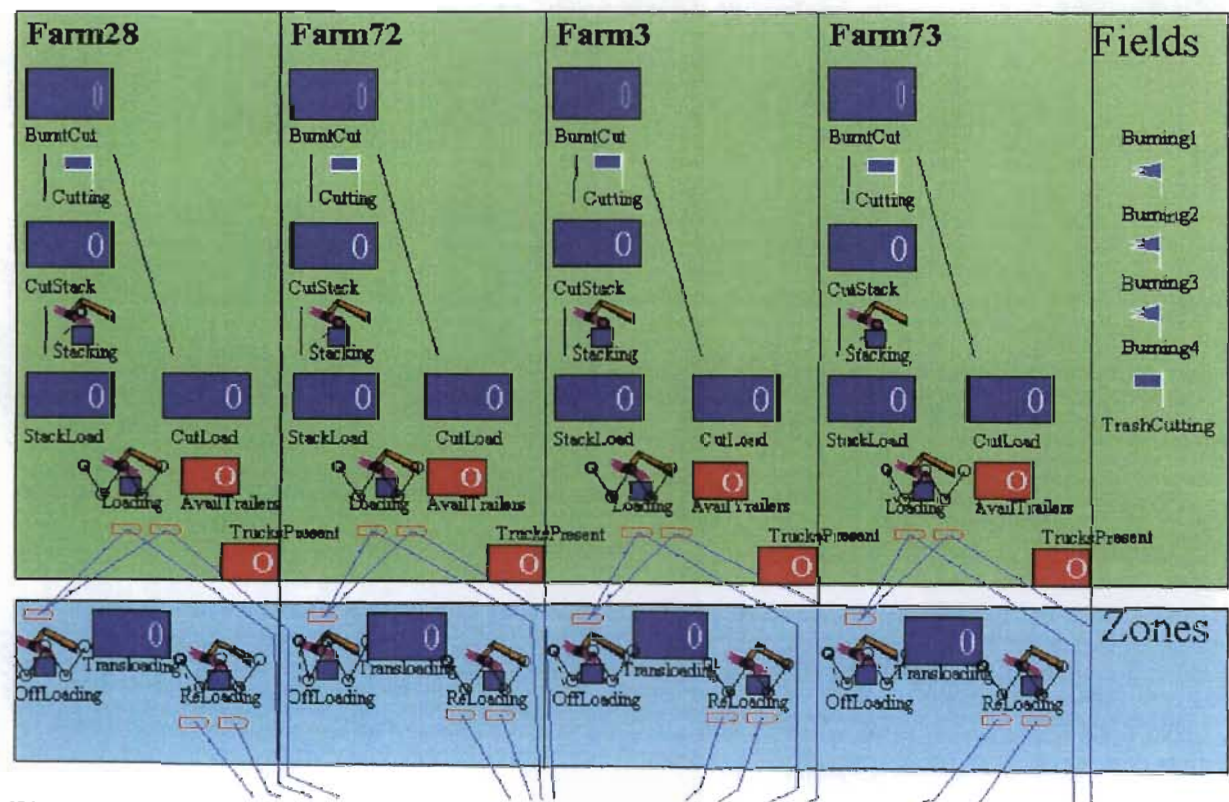
Figure 8.   Animation of harvesting and transport operations

The icons between the stockpiles represent processes such as cutting, stacking, loading, offloading and reloading (the last two in the transloading zones). These icons are red when the process is occurring, blue when it is not occurring due to lack of cane entities and yellow when the process is scheduled not to occur. The burning icons on the right do not relate to individual farms - they only represent when the various burn schedules start and stop.

The red variable boxes represent the number of tractor-trailer units and trucks available for loading in the fields and on the zones, that are not actually being loaded. The transport units actually being loaded appear on or next to the loading icons. The blue lines between the red rectangles represent the routes from field to zone and from zone to mill along which the transport units travel with the trip time calculated by the model. The length of the lines is not proportional to the distances travelled.

The millyard animation illustrated in Figure 9 is more self explanatory as it is a less stylised representation of the operations occurring in the model. Trucks entering the millyard at the weighbridge travel along the blue route lines to the various offloading points. Cane is transferred at the offloading point to the mill tables or stockpiles which are represented by levels which fill or empty as the tonnage on the tables or in the stockpiles increases or decreases. Variable displays also reflect the tonnage in the stockpiles or on the tables and other variables such as the cumulative tonnage crushed, the current crushing rate and the numbers of vehicles in the various offloading point queues are also displayed. The large-grab gantry-crane which can be seen over the east table in Figure 9 and the bundle-offloading gantry-crane are depicted by icons that change colour depending on whether the resources are busy, idle or off shift. The large-grab gantry-crane icon moves between the ground and bundle stockpiles and the west table in a similar manner to the front end loaders that move between the dummy spiller area, the ground stockpile and the east and west shutes feeding the mill.
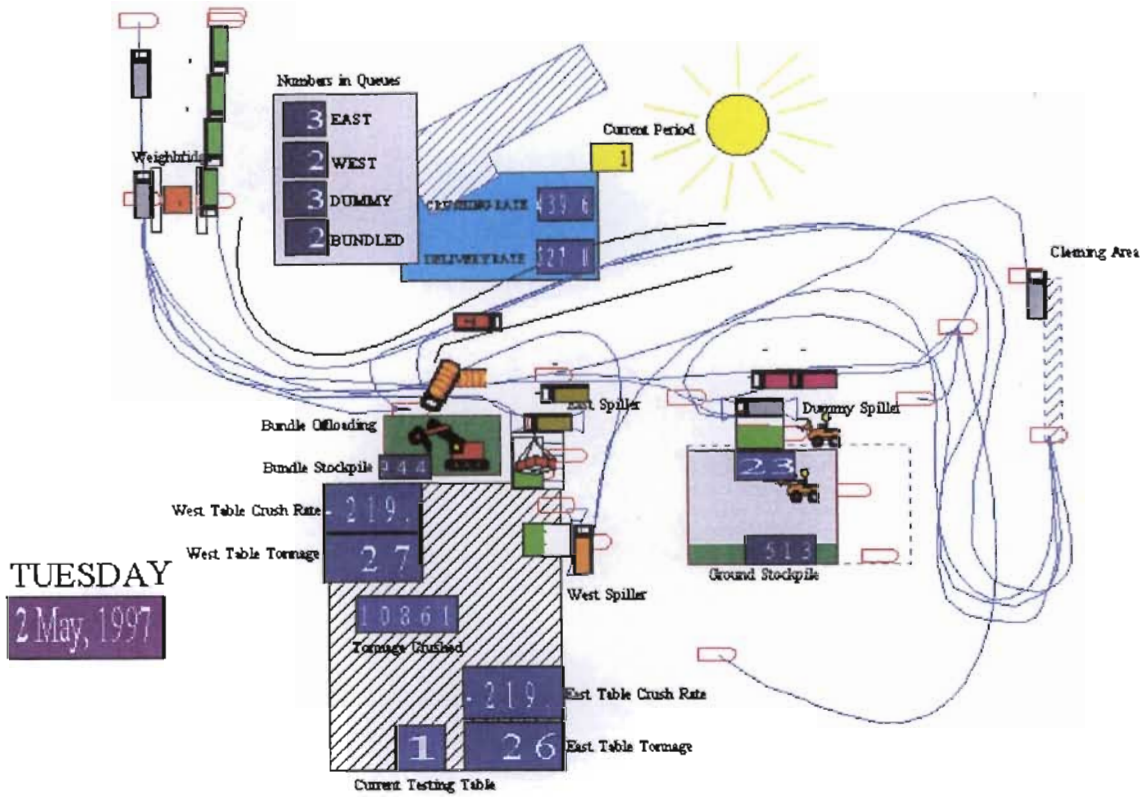
Figure 9. Animation of millyard operations

5.5 Experimental Reports

The primary experimental report for the harvest-to-crush delay model was the time that the one ton cane entities spent in the system, since this was defined as the measure of effectiveness by which the extent to which the objectives of the model had been achieved could be determined. However, other reports were necessary to highlight problems in the system that were preventing the objectives of the model being achieved. As such, the time that the cane spent in the various stockpiles in the system, the tonnage in these stockpiles and the utilization of various resources in the system was also recorded. Other variables that were recorded were the time between truck arrivals at the mill gate and the time that the trucks spent at the mill. An example of the summary output for a week in a particular model run is shown in Appendix C. The values of the various variables over time were recorded in data files that could be analysed after the model runs.

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5.6 Interpretation of Simulation Output

Due to the use of frequency distributions in simulation models to more realistically represent process times, the summary statistics generated for each simulation are in fact random variables and as such, statistical analysis is required to provide point and interval estimates of the parameters of interest. The approach used to analyse a simulation model's results depends on whether the system is terminating or non-terminating. A terminating system has a fixed starting condition, to which it returns after each termination, and an event defining the natural end of the simulation. A non-terminating system has neither a fixed starting condition nor a natural ending point. The analysis of terminating systems is reasonably simple, since the summary values from each replication of the simulation can be assumed to be statistically independent and, by the Central Limit Theorem, normally distributed. Therefore, if sufficient replications are performed, these values can be used to construct confidence intervals on the mean. However, for non-terminating systems, there is no event that causes the system to return to a fixed starting condition and therefore it is the steady-state behaviour of the system that is of interest. The initial transient phase of the non-terminating systems that varies with the selected starting conditions thus has to be truncated from the results and the remaining observations can then be divided into equal, non-overlapping batches. If these batches are sufficiently large, the means of adjacent batches will be approximately independent and can then be used to construct confidence intervals. The batch size required to achieve independence is a function of the correlation structure of the system response and the rule of thumb is that the batch size should be at least 10 times as large as the largest lag for which the correlation between observations remains significant (Pegden *et al.*, 1995).

For the harvest-to-crush delay model, a five week long run was executed and the time in system data were examined using the Arena Output Analyser. A plot of the time in system for cane stored in the ground stockpile before being fed into the mill is shown in Figure 10. The moving average or smoothed line in Figure 10 has an interval of 100 observations and it can be seen that the initial condition bias only appears to last for approximately the first 40 hours of the simulation. Therefore the first week of data recorded was truncated to ensure that the initial condition bias did not affect the results. The correlogram for the remaining data was plotted as
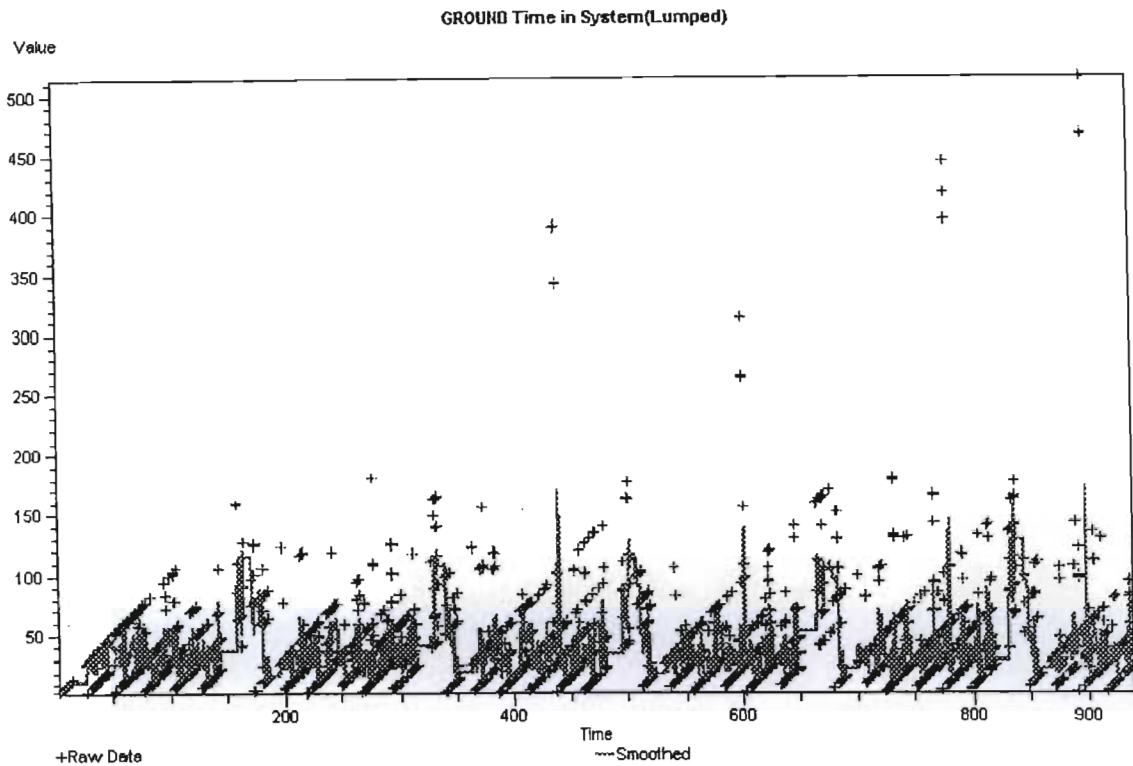
Figure 10. Time in system plot for cane stored in ground stockpile

shown in Figure 11. From this plot, it was determined that the largest lag for which the correlation between observations remained significant was approximately 600. Therefore, a batch size of 6000 was chosen. Since the five week (840 hour) run produced 64466 observations, 78 hours of simulated time would be required to produce the batch of 6000 observations. This time was rounded off to 168 hours or one week of observations per batch for convenience and because the system does operate on a basic cycle of a week. A run length of 21 weeks was therefore selected so that the first week of data could be truncated and 20 batch means would then remain so that the t-statistic would be reasonably small when calculating the confidence intervals.

During the process of formulating or developing the model, continual verification was performed and once the development was complete it was necessary to validate the model. These processes are discussed in the following chapter along with the application of the model to numerous different experimental runs.

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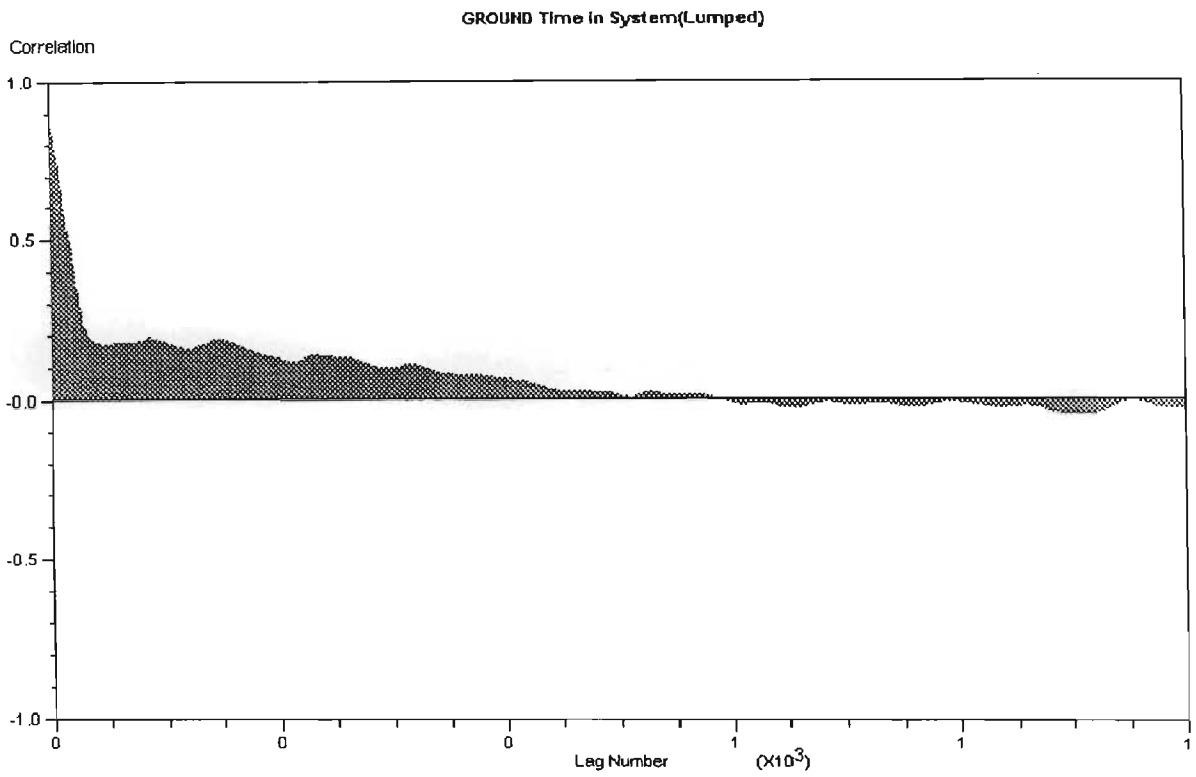
Figure 11.   Corelogram of time in system data for cane stored in ground stockpile

6. MODEL VERIFICATION, VALIDATION AND APPLICATION

In the context of simulation modelling, the process of determining the correctness of a model's operation typically consists of two separate functions: verification and validation. Verification is the process of determining that a model operates as intended and mainly involves finding and removing unintentional errors in the logic of the model. Validation is the process of reaching an acceptable level of confidence that the inferences drawn from the model are correct and applicable to the real world system being represented. Through validation it is attempted to determine whether the simplifications and omissions of detail, which have been knowingly and deliberately made in the modelling process, have introduced unacceptably large errors in the results. (Pegden *et al.*, 1995)

6.1 Model Verification

Pegden *et al.* (1995) state that, to a large extent, the complexity of the verification process increases with the size of the model. Because of the large size of the model of the sugarcane harvesting and delivery system it was important to test the model as it was developed and to correct as many errors as possible at each stage of development. This was also the reason that the model was initially broken up into a harvesting and transport section and a millyard section.

The primary device used to verify the model was to check that, given reasonable input, the model gave reasonable output in such areas as the time that cane spends in the system, the tonnage in various stockpiles and the utilization of the various resources in the system. Although the system is non-terminating, it does operate on a basic cycle of a week and it was therefore important that most of the stockpiles in the system returned to near empty or some equilibrium level at the end of each week. For example, the tonnage left in the transloading zone stockpiles at the end of each week in the representation of the existing harvesting and delivery system varied from 1500 to 2000 tons. This figure represents about 17 to 23 tons per farm which can be explained by the fact that part loads would not be transported off the zone. The tonnages that built up in the various stockpiles also proved useful in isolating the errors that occurred, since a bottleneck usually indicated where in the logic the mistake had been made.

6.2 Model Validation

Having established that the individual components of the model behave reasonably and that the model operates as intended during the development stage, it was then necessary to compare the modelled system to the real system to build confidence in the simulation.

6.2.1 Model input for existing mill area situation

In order to be able to compare the modelled and real systems it was necessary to set up the model input to approximate the existing harvesting and delivery systems used in the Sezela mill area as closely as possible. This was done by configuring the input spreadsheet according to the data collected in the grower survey and the relationships developed from these data. Certain inputs such as farm DRD, delivery schedules and whether a farm delivers sugarcane to the mill in bundle or loose form were known from mill records. The total tonnage delivered to the mill per week, as calculated by summing the DRDs for each farm, was 63355 tons and the target tonnage used to determine the rate at which the mill crushes was set at 67000 tons. The following relationships, based on data from the grower survey, were used to estimate unknown inputs on farms that had not been surveyed:

The burning schedule was sampled from a discrete distribution with a 46% chance of being burn schedule 1, 35% chance of being burn schedule 2, 11% chance of being burn schedule 3, 4% chance of being burn schedule 6 and 4% chance of being burn schedule 7.

The value of the variable SplitBundle, which determines whether or not bundles formed infield are split on the zone, was determined as follows:

If the zone loading type was bundled and the cane was to be delivered to the mill in bundled form, split bundle was set to 0

If the zone loading type was bundled and the cane was to be delivered to the mill in loose form, split bundle was set to 1

If the zone loading type was grab, the value for split bundle was sampled from a discrete distribution with 63% chance of being 0 and 37% chance of being 1

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The number of infield tractor-trailer units used on a farm was calculated by rounding off the following equation to the nearest integer, with a minimum of 1:

$$Number\ of\ Infield\ Trailers = \begin{cases} 0.016 * DRD & if\ Zone\ Load\ Type\ is\ Grab \\ 0.038 * DRD & if\ Zone\ Load\ Type\ is\ Bundle \end{cases} \quad (7)$$

The r-square values for these two equations were 72% and 92% respectively.

The number of infield loading units used on a farm was set equal to the number of infield trailers if the zone loading type was bundle, since bundle trailers are usually self-loading. If the zone loading type was grab, the number of infield loading units was calculated by rounding off the following equation to the nearest integer with a minimum of 1:

$$Number\ of\ Infield\ Loaders = 0.012 * DRD \quad (8)$$

The r-square value for this equation was 77%.

The number of zone offloading units used on a farm was set equal to the number of infield trailers if the zone loading type was grab, since the loose cane trailers are usually self-offloading. If the zone loading type was bundle, the number of zone offloading units was calculated by rounding off the following equation to the nearest integer with a minimum of 1:

$$Number\ of\ Zone\ Offloaders = 0.0076 * DRD \quad (9)$$

The r-square value for this equation was 67%

Finally, the number of zone reloading units used on a farm was set to 1 if the farm DRD was less than 100 tons and 2 if the DRD was greater than or equal to 100 tons. The model was then run using this input for a 21 week period and the results were processed according to the method described in the previous chapter.

6.2.2 Comparison of mill arrival distributions

In December 1997, staff at the Sezela mill recorded truck arrival times at the mill over a three-week period in order to determine the distribution of arrivals through the week. This exercise provided real system data with which to compare the output of the harvesting and transport

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section of the model, since the output of this section of the model was effectively truck arrival at the mill gate. With the model input set up to approximate the existing harvesting and delivery system as closely as possible, the arrival times of truckload entities in the model were recorded and used to construct the simulated arrivals distribution. The distributions of truck arrivals at the mill on an hourly basis through the course of a week for the observed and simulated data are shown in Figure 12. For the observed data, week 1 and week 3 of the three-week period of the survey were averaged, while for the simulated data, the 20 weeks of the simulation were

Observed Arrivals

Simulated Arrivals
Existing Delivery Plan
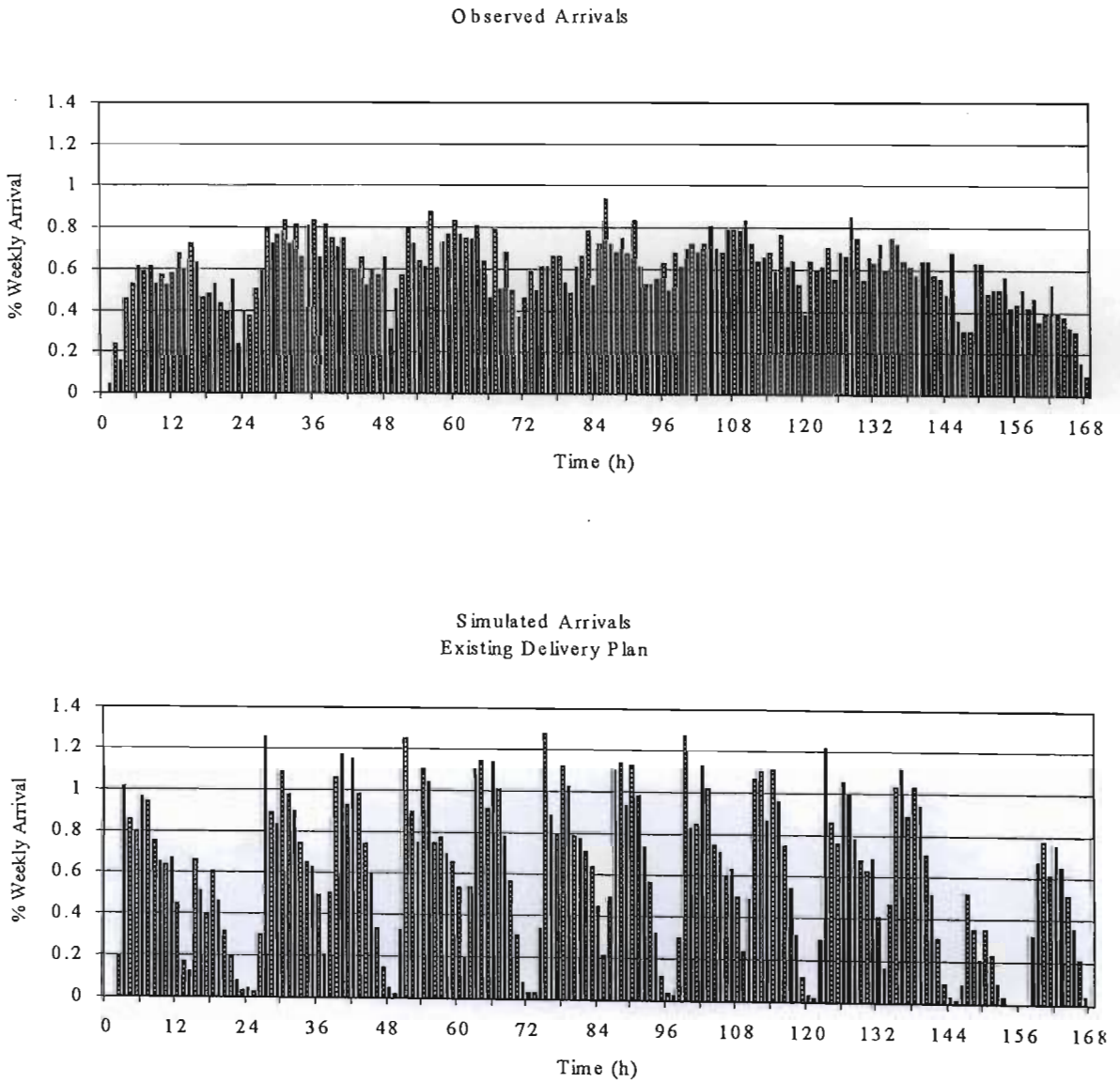
Figure 12.   Comparison of simulated and observed weekly mill arrival distributions

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averaged. Week 2 of the survey period had a number of disruptions in deliveries and was thus not used for comparison. It can be seen that the observed arrivals were much more evenly distributed through the week than the simulated arrivals which displayed sharp drops at the beginning and end of each twelve-hour period. This can be explained by the manner in which the truck dispatching system in the model was based on a twelve-hour period - when the deliveries scheduled for each twelve-hour period had been performed, no more deliveries would occur until the next twelve-hour period. Deliveries tended to be completed somewhat early within the twelve-hour periods because the harvesting and delivery systems modelled have extra capacity to cater for equipment breakdowns and weather and managerial delays that occur in the real system but were not simulated in the model because of the complexity they would have added. However, it can also be seen that the general pattern of arrivals, with fewer arrivals at the beginning and end of the week and a drop in the number of arrivals at the beginning of each day, is similar for both the simulated and observed arrivals.

The distribution of truck arrivals for the observed and simulated data on a twelve-hourly basis is shown in Figure 13. The distribution of planned deliveries on a twelve-hourly basis as
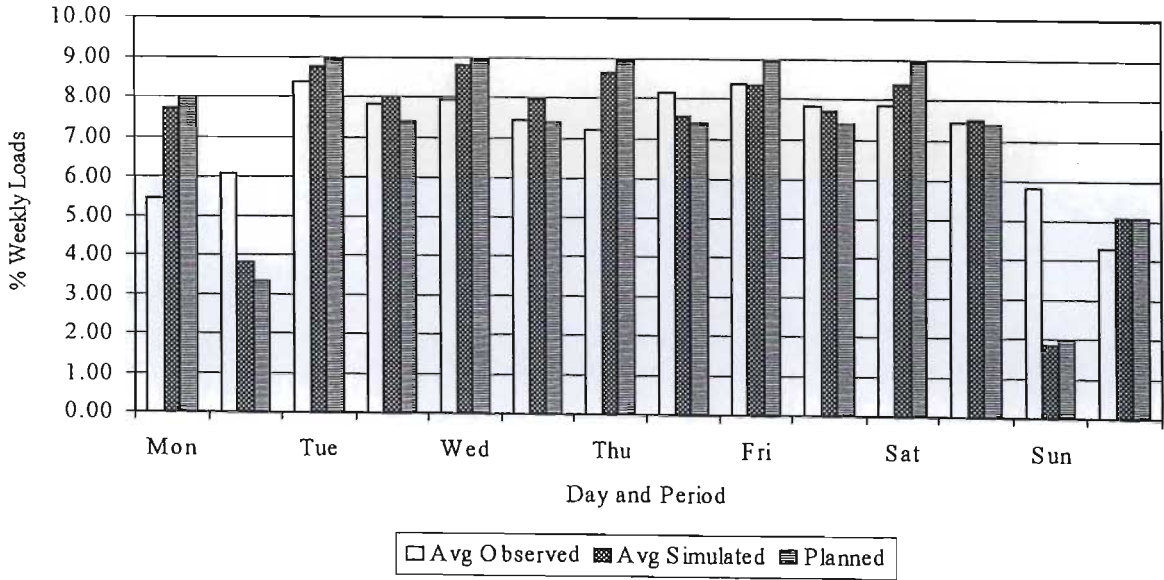

Figure 13. Comparison of mill arrival distributions on a twelve-hourly basis

calculated from the DRD and delivery day and period for each farm is also shown in Figure 13. It can be seen that the planned and simulated arrivals correspond very closely. This is reasonable, since the dispatching system in the simulation is based on the delivery plan, but it serves to confirm once again that the model is operating as intended. It can also be seen that the observed arrivals are more evenly distributed through the week than the planned or simulated arrivals, which indicates that the mill's delivery plan is not perfectly adhered to by the growers and hauliers. The biggest deviations of the simulated arrivals from the observed arrivals occur during the Sunday day period and the Monday day and night periods. The higher than planned deliveries during the Sunday day period can be attributed to growers and hauliers making up loads that were not able to be delivered during the week and the lower than planned deliveries on during the Monday day periods can be attributed to growers often not having left over cane in the fields or transloading zones from Saturday harvesting. The higher than planned Monday night period deliveries can also be also be attributed to this 'startup effect' as growers and hauliers try to make up deficit deliveries from the Monday day period. However, the similarities in simulated and observed data are once again sufficient to indicate that the model is operating reasonably.

6.2.3 Comparison of harvest-to-crush delays

Another test used to build confidence in the model was to compare simulated harvest-to-crush delays with delays recorded by Miller-Cum-Planter (MCP) farms in the Sezela mill area. The MCP farms record the time at which sugarcane is burnt, as well as the times at which it reached various stockpiles en route to the mill, on the consignment ticket that travels with each bundle or load of cane. The delay calculated from these data is effectively the harvest-to-millgate delay. For the first twenty-two weeks of the 1998/99 season, the weekly average delay for the 10 MCP farms in the Sezela mill area ranged from 48 hours to 72 hours with a mean of 57 hours (Horne 1998). For the twenty-week simulation with existing system input, the mean weekly harvest-to-crush delay for cane offloaded by spiller was 35.1 hours, with a 95% confidence interval half width of 0.20 hours. The MCP cane would mostly fall into the category of spiller cane offloaded directly onto the spiller tables, since 78% of all loose cane is offloaded in this manner and all MCP deliveries are at night when there are fewer trucks arriving at the mill and therefore, less likelihood of the truck being routed to the dummy spiller. The harvest-to-crush delay for directly

spiller offloaded cane would effectively be the same as the harvest-to-millgate delay, since the extra time taken to offload the cane in the yard is negligible in comparison to the magnitude of the overall delay.

It would thus appear that the model is underestimating the harvest-to-crush delay, but it must be kept in mind that the model does not account for inclement weather, mill breakdowns, transport breakdowns and labour problems which all contribute to increased delays in the real system. The model also assumes that burnt cane is cut as soon as it and cutters are available and cut cane is stacked or loaded as soon as it and stacking or loading resources are available. In reality, many growers will delay cutting or loading of cane till the following day, if they think that there are not enough daylight hours left to process all the cane in a field and this also increases real system delays. When considering these facts and the statement by certain growers that 48 hours is an acceptable delay when the system is operating smoothly (Horne, 1998), 35 hours seemed a reasonable estimate of the harvest-to-crush delay for spiller offloaded cane and the model therefore appears to be simulating harvest-to-crush delays in an acceptable fashion. It should also be noted that the stated purpose of the model is to compare systems and not estimate the absolute harvest-to-crush delay that any particular system will produce and if the model is operating in a reasonable manner, this should be sufficient for the purposes of comparison of systems.

6.3 Application of the Model

Having established confidence in the operation of the model, the next step was to use the model to investigate strategies or methods of reducing harvest-to-crush delays. Numerous strategies and methods had been suggested by the literature reviewed as well as by personnel in the South African sugar industry. However, due to time constraints, the number of methods that could be investigated in this study was limited. The following strategies were chosen as being likely to have the most significant effects on harvest-to-crush delays or as being of particular interest to sugar industry personnel involved in the project.

6.3.1 Balanced delivery plan

By balancing sugarcane deliveries to the mill through the course of the week, it was hoped t
reduce the period in which there was congestion at the mill, thus decreasing the turnaround tin:
for vehicles offloading in the mill. These vehicles would then be available more quickly t
remove sugarcane from the transloading zones and in this way reduce harvest-to-crush delay:
The easiest way to balance deliveries within the constraints of the despatching system used in th
model was to set all farms to a 24 hour a day, 7 day a week delivery schedule. All other input
were left as for the existing situation scenario.

6.3.2 Improved management of burning schedules

If all farms were using a daily burn schedule, the amount of time that burnt cane spends standin
in the field waiting to be cut would be significantly reduced, since there would be no overnigl
carryover of cane to ensure that there is cane available to be cut on days when no burning i
performed. Furthermore, if all cane is burnt in the morning and none in the evenings, burn to cu
delays would be reduced for the same reason. Daily burning involves greater management effo
since smaller areas have to be burnt which means that field sizes and fire breaks have to be we
planned, and it also involves the risk of not having burnt cane to cut if weather condition
preclude burning in the morning. To determine the effect of improved burning schedu:
management on harvest-to-crush delays, all farms in the model were set to operate on bur
schedule 1, which is the daily burning, mornings only schedule and all other inputs were left ;
for the existing situation scenario. The effect of removing the burning process from the syste
altogether was investigated in a separate run by putting all farms in the model onto cutting gre
cane and leaving all other inputs as in the existing situation scenario.

6.3.3 Farms delivering direct to the mill

If more farms deliver sugarcane directly to the mill without transloading, the delays involved i
offloading, reloading and storage of cane on the transloading zones will be reduced. Since mo
of the farms in the Sezela mill area are at a distance from the mill that makes delivery of cane l

tractor-trailer units impractical and there are limited facilities for offloading such units in tl millyard, it was assumed that any direct transport would involve truck-trailer units being load infield. It was also assumed that farms that split bundles formed infield for loose cane reloadin on the transloading zone, would not change to direct delivery since this would involve changin their harvesting system so that they could load loose cane rather than bundles infield. Changin such harvesting systems would involve getting rid of self-loading bundle trailers and replacin them with Bell loaders. Because it is assumed in the model that infield operations only occi during the day and not on Sundays, the delivery schedules of a number of the farms that had bee changed to direct delivery had to be altered. This created an imbalance in day and nigl deliveries, so all day delivering farms that still were set to practice transloading were changed t night delivery. Finally, several farms' delivery schedules were changed to balance the tonnas delivered by the individual hauliers through the week. In the end then, 34% of the tonnas delivered to the mill was set to be delivered direct and the day/night balance of deliveries w; approximately even, but very much less cane than in the existing situation scenario was schedule to be delivered on a Sunday. All other inputs were left as for the existing situation scenario.

6.3.4 Matching harvesting, delivery and milling cycles

The idea behind matching the various cycles in the harvesting, delivery and milling system w; to reduce the amount of stockpiling necessary to allow for the differences in the schedules. Thr different alterations of the schedules were investigated and all inputs were left as for the existir situation scenario except where specified.

Because of the delivery schedule distribution that resulted from the manipulations required in tl scenario involving more farms delivering direct to the mill, the first scenario looked at in tl investigation of the effect of matching milling, delivery and harvesting schedules on harvest-tc crush delays was the case of all farms delivering Monday to Saturday. This would bring tl delivery schedule more in line with harvesting schedules and would also give an indication whether or not the altered delivery distribution in the previous scenario (which had very muc less tonnage delivered on a Sunday) had any effect on the harvest-to-crush delays estimated that scenario.

The second scenario was to investigate the effect of harvesting Monday to Sunday to match the milling cycle. This involved having to make changes to the model itself. In the harvesting processes, the burning, cutting and stacking process schedules were altered to include infield operations being performed on a Sunday and the dispatching algorithms were altered to allow for the provision of cane to be delivered from Sunday harvesting. The delivery schedules in the input spreadsheet were also changed to Monday to Sunday for all farms and all farms were set to a daily burn schedule to make 7 days a week harvesting possible. Since the DRDs specified for the individual farms were for 6 days a week, the model was setup so that 6/7ths of the DRD should be cut and delivered each day.

The third scenario was to alter the milling cycle to Monday to Saturday to match Monday to Saturday harvesting and delivery schedules. To implement this, the crush plan, which is used to calculate the rate at which cane is removed from the spiller tables, was altered so that 15% of the target tonnage would be crushed on a Monday, 18% is crushed each day Tuesday to Saturday and 0% is crushed on a Sunday. This implied that the maximum crushing rate required to achieve the 67 000 tons a weeks target tonnage increased from 419 tons/h to 500 tons/h. All farms were put onto a Monday to Saturday delivery schedule to match the deliveries to the harvesting and milling cycles.

To make a comparison between Monday to Sunday harvesting and Monday to Saturday crushing as ways of matching harvesting and milling cycles it was necessary to rerun the Monday to Saturday crushing scenario with all farms assigned to daily burn schedules as was necessary in the Monday to Sunday harvesting scenario. All other inputs were set up as for the first Monday to Saturday crushing scenario.

6.3.5 Use of single central haulier to minimise vehicle numbers

Another suggestion for reducing the congestion at the mill and in this way making vehicles available more quickly to remove cane from the transloading zones, thus reducing harvest-to-crush delays, was to reduce the total number of vehicles operating in the area. The premise was that many of the growers providing their own transport are not fully utilising their vehicles and

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if there was a single haulier providing transport for the whole mill area, the utilisation of the vehicles could be maximised and the number of vehicles in the area could thus be minimised. Three runs with the single haulier setup in the input spreadsheet with 100, 80 and 75 vehicles available respectively were executed.

6.3.6 Organisation of farms into harvesting groups

Numerous farms in the Sezela mill area have DRDs less than 30 tons which implies that cane has to be accumulated for two or more days to make a full truckload of 24 to 35 tons. If cane is cut every day, as it is in the harvesting algorithm of the model, some cane will incur an extra 24 or 48 hours of delay before it can be taken off the transloading zone. Furthermore, it is very difficult to burn the small areas required for such DRDs on a daily burn schedule since fields would need to be set out with many fire breaks and small panels. Therefore, organisation of farms into harvesting groups with larger DRDs should have benefits in reducing harvest-to-crush delays. In the input spreadsheet, the 85 original farm combinations were joined into harvesting groups with at least 100 ton DRDs. There were thus finally 51 harvesting groups. The farms were grouped within their areas, as defined by the Mill Group Board estimate and with the same haulier, wherever possible. Harvesting systems and schedules were assigned according to the farms with the largest DRD within the group and numbers of infield transport and loading equipment were calculated according to the equations developed from the grower survey data. Since all farms had a DRD of 100 tons or more, it was assumed that all farms would be able to burn on a daily basis.

6.3.7 Idealised harvesting and delivery system

In order to determine the theoretical minimum harvest-to-crush delay that could be obtained for the Sezela mill area, the model input was set up with the most effective of the previously investigated strategies for reducing delays. All farms were organised into harvesting groups as described in the previous subsection and assigned to cut green cane, Monday to Sundays. The farms that could deliver direct to mill with their current harvesting systems were assigned to do so as described in section 6.6.3 and all farms were set to deliver cane 7 days a week.

6.3.8 Effect of mill breakdowns

The final scenario investigated was the effect of mill breakdowns on harvest to crush delays and once again, changes had to be made to the model itself. Mill breakdowns were assumed to occur at intervals described by an exponential distribution with a mean of 24 hours. Two classes of breakdown were modelled. An initial breakdown period of 15 to 45 minutes was sampled from a triangular distribution with a mode of 30 minutes. It was then assumed that there was a 20% chance that the breakdown could last longer than 45 minutes. The additional breakdown period could last from 0 to 4.25 hours and was therefore sampled from a uniform distribution with minimum 0 and maximum 4.25 hours. For the initial breakdown period, no cane was fed into the mill (the rate was set to zero) and all trucks arriving at the gate were routed to the dummy spiller or bundle offloading points as appropriate. Trucks already in the direct spiller queues were redirected to the dummy spiller. If the breakdown went on for more than 45 minutes, then blockages were brought into effect which would prevent trucks from being sent to the mill from the transloading zones as well as preventing the dispatching of further trucks to the zones. After the breakdown period, the mill feeding rates were reassigned to their original values and the blockages, if implemented, were removed.

In the next chapter, the results of the various runs described here are presented and the validity and implications of the results are discussed.

7. RESULTS AND DISCUSSION

The point estimates of overall average weekly harvest-to-crush delay for the various experimental runs performed with the integrated model are presented in Table 4 below along with the minimum, maximum and 95% confidence interval half width for each value. These results are discussed in this chapter as well as certain other results recorded in different experimental runs. The cost implications of harvest-to-crush delays are also investigated.

7.1 Model Run Results

All the run results are compared to the results from the initial run of the model in which the input was set up to approximate the existing situation in the Sezela mill area. The existing situation run took approximately 14 hours to execute and the run times for the other scenarios was of the same order of magnitude, depending on the tonnage levels of the various stockpiles. The greater the average tonnage in the stockpiles, the greater was the run time.
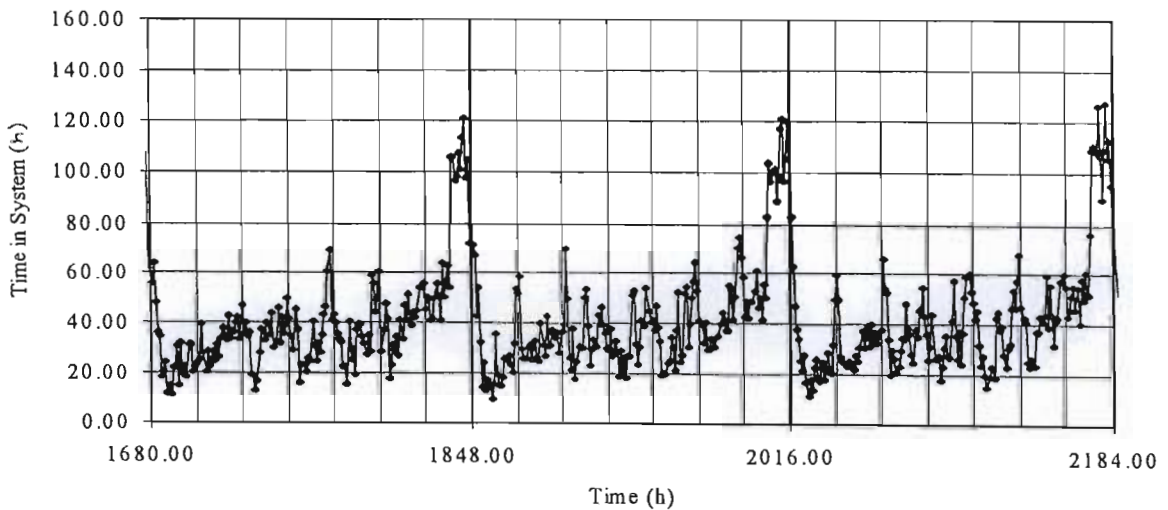
Table 4.   Average weekly harvest-to-crush delays

Scenario	Average Weekly Delay (h)	Minimum (h)	Maximum (h)	95% Confidence Level Half Width (h)
Existing Situation	38.2	37.6	39.2	0.16
Balanced Delivery Plan	39.7	39.0	40.5	0.15
Daily Burn Schedule	29.7	29.1	30.1	0.15
Cutting Green Cane	25.8	25.3	26.4	0.14
More Farms on Direct Delivery	35.0	33.7	36.9	0.35
Mon-Sat Deliveries	36.0	35.5	36.8	0.13
Mon-Sun Harvesting	19.4	18.9	19.7	0.09
Mon-Sat Crushing	27.4	26.9	28.1	0.14
Mon-Sat Crushing with Daily Burn Schedule	18.5	18.2	18.7	0.08
Single Central Haulier (100 vehicles)	39.2	38.6	39.7	0.18
Single Central Haulier (80 vehicles)	39.8	38.7	41.7	0.39
Harvesting Groups	26.3	25.8	26.9	0.13
Idealised System	12.0	11.9	12.1	0.04
Mill Breakdowns	40.5	38.7	42.7	0.56

Examination of the results in Table 4 show that the 95% confidence interval half widths are very small in relation to the average weekly delays - of the order of 1% of the average delays. This indicates that the weekly average delays calculated from the runs were reasonably constant for any particular scenario and can be taken as reliable estimates of the true mean of the weekly average delays.

7.1.1 Existing situation

Some of the results of the run of the model with the existing situation input were presented in Chapter 6 where the verification and validation of the model were discussed. A point to be noted about the point estimate of overall average weekly harvest-to-crush delay is that it is calculated from weekly means which are the means of values that vary quite widely through the course of each week. In Figure 14 the hourly average time in system or harvest-to-crush delay is shown for a typical three week period in the run of the model and it can be seen that the values vary from day to night as well as building up through the course of the week.

Figure 14.   Hourly average harvest-to-crush delays over a three week period for the existing situation scenario

The point estimate of overall average weekly harvest-to-crush delay is broken down into point estimates of the average weekly delays incurred by cane in the various stockpiles in the system in Figure 15. Although individual stockpiles are recorded for each farm, the stockpiles referred to here are the aggregate stockpiles for the whole mill supply area. The NightBurntCut stockpile referred to in Figure 15 represents cane burnt in the evening and standing in the field waiting to be cut. The BurntCut stockpile represents cane burnt in the morning and standing in the field waiting to be cut. The CutStack stockpile represents cane that has been cut and is waiting to be stacked and the DCutLoad stockpile represents cane that has been cut and is waiting to be loaded before being transported directly to the mill. Cane in the TCutload stockpile will be transloaded before being transported to the mill. The DStackLoad and TStackLoad stockpiles represent cane that has been stacked and is waiting to be loaded before being transported either directly to the mill or to a transloading zone. The Infield Transport stockpile represents cane that is currently being transported from field to zone where it is either added to the Bundle Transload stockpile or the Spiller Transload stockpile depending on whether it is to be delivered to the mill in bundle form or not. Cane being transported either from the field or zone to the mill in trucks is taken to be part of the Road Transport stockpile. Once in the millyard, cane offloaded at the bundle off loading point is added to the BundleStore stockpile while cane offloaded at the dummy spiller is added to the GroundStock stockpile. The one ton entities of cane do not progress through all
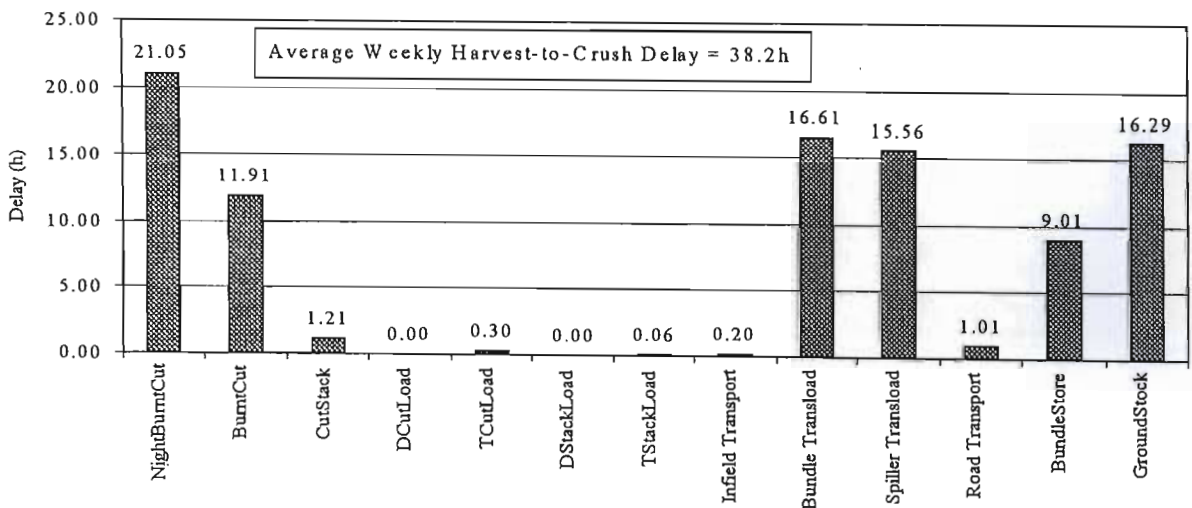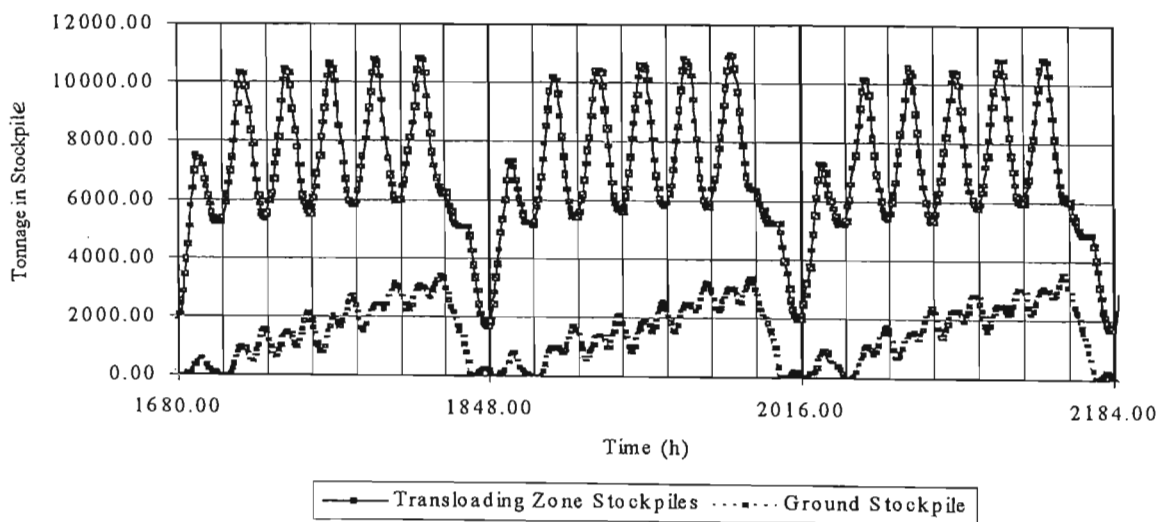

Figure 15. Stockpile delays for the existing situation scenario

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these stockpiles, only those appropriate to the harvesting and transport systems being used on the particular farm from which the cane is sourced.

The very short delays for cut or stacked cane waiting to be stacked or loaded are due to the way in which the model immediately processes cut or stacked cane, as is mentioned in Chapter 6. The long delays incurred in the NightBurntCut and BurntCut stockpiles are due to the practice of only burning cane every second or third day that occurs on many farms in the Sezela mill area. Cane burnt on a Monday morning may have to wait until Tuesday or Wednesday afternoon before it is cut, thus incurring an additional 24 to 48 hour delay. The long delays in the transloading zone stockpiles are caused by the differences in harvesting and delivery schedules - harvesting occurs Monday to Saturday and on some farms, delivery occurs Tuesday to Sunday or seven days a week, so stockpiles have to be built up in the transloading zones during the week to ensure that there is cane to transport on a Sunday. A similar reasoning can be applied to the long delays in the millyard stockpiles. The mill crushes Monday to Sunday and, as was seen in Figure 13 in Chapter 6, the bulk of deliveries to the mill arrive from Monday to Saturday, and so cane has to be built up in the millyard stockpiles during the week to supply the mill on a Sunday. The build up in stockpiles can also be seen in Figure 16.
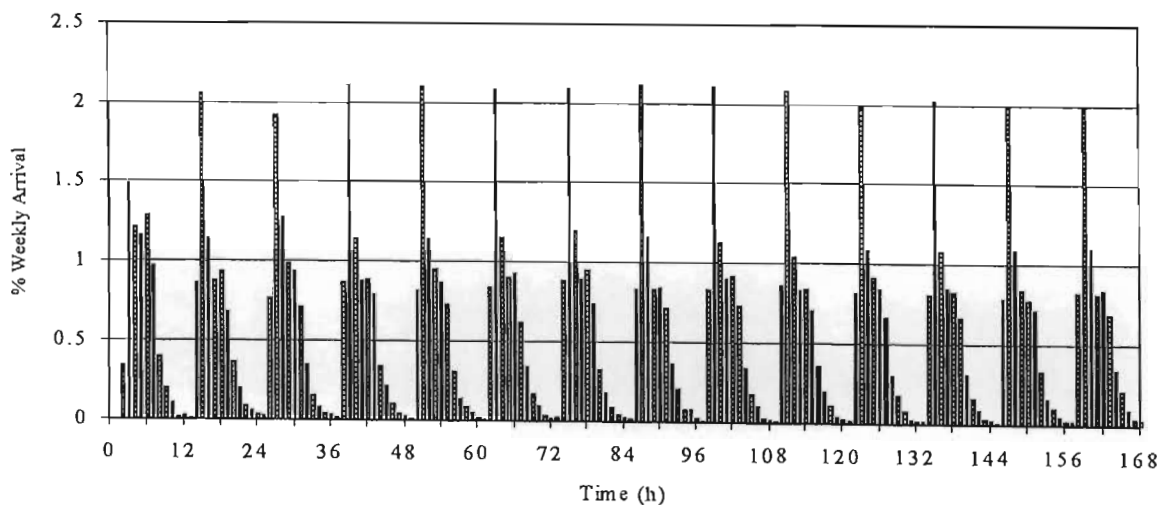

Figure 16. Hourly average stockpile levels over a three week period for the existing situation scenario

7.1.2 Balanced delivery plan

From Table 4 it can be seen that the point estimate of average weekly harvest-to-crush delay for the balanced delivery plan scenario is greater than that for the existing situation scenario. The estimated mean difference was -1.5 hours with a 95% confidence interval half width of 0.22 hours which implies that the difference is significant at the 95% confidence level, since the confidence interval does not include zero. This means that the strategy of trying to decrease congestion at the mill and therefore harvest-to-crush delays by using a balanced day-night, seven day a week delivery plan was not successful. One possible explanation is that, although the truck dispatching algorithm in the model ensures that the day-night and weekday distribution of deliveries to the mill is balanced, it does not ensure that the deliveries are evenly distributed within a particular 12 hour period and therefore congestion may still occur at periods of peak arrivals as illustrated in Figure 17.

Furthermore it can be seen from Figure 18 that some of the overall harvest-to-crush delay is transferred from the millyard stockpiles to the transloading zone stockpiles. This is because the delivery plan now more closely matches the crushing cycle, but is further removed from the Monday to Saturday harvesting cycle and therefore less stockpile has to be built up in the

Figure 17.   Average hourly arrivals distribution for the balanced delivery plan scenario

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millyard and more in the transloading zones, as can be seen in Figure 19. In Figure 18 and all similar graphs to follow, the data labels refer to the current scenario and not the existing situation scenario which is illustrated for comparison purposes.
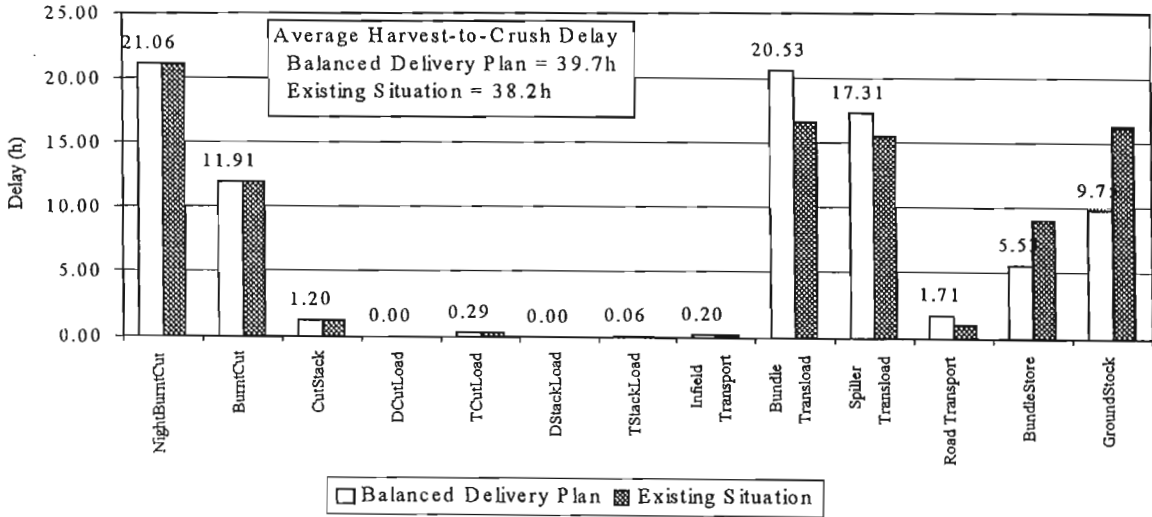

Figure 18. Stockpile delays for the balanced delivery plan scenario
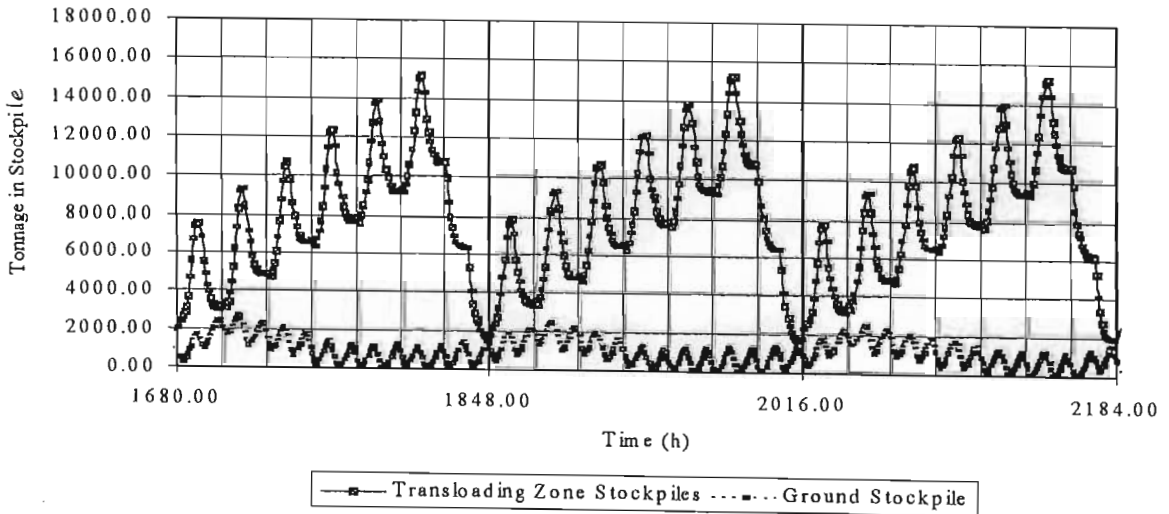

Figure 19. Stockpile levels over a three week period for the balanced delivery plan scenario

7.1.3 Improved management of burning schedules

The estimated mean difference between the point estimate of overall average weekly harvest-to-crush delay for the daily burn schedule scenario and that for the existing situation scenario is 8.5 hours with a 95% confidence interval half width of 0.21 hours. In Figure 20 it can be seen that the main decrease in delays is in the stockpiles of burnt cane waiting to be cut. This is because there is no burnt cane having to wait overnight to be cut in the morning or for a twenty four hour period if it has been burnt in the morning and is only scheduled to be cut the following day. One problem with this scenario is that, on farms with DRDs less than approximately 30 tons, even if cane is burnt on a daily basis, it will have to wait a day or two in the field or transloading zone until sufficient cane has been accumulated to provide a full load for a truck. Therefore, for the full effect of better management of burning schedules to be useful, farms with smaller DRDs need to practise some sort of group harvesting
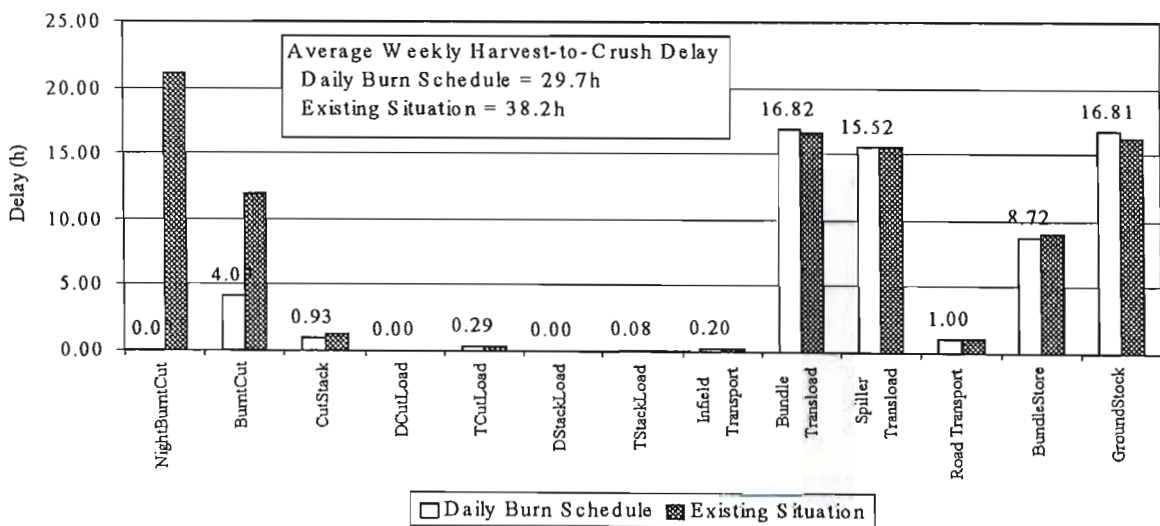

Figure 20.   Stockpile delays for the daily burn schedule scenario

The estimated mean difference between the point estimate of overall average weekly harvest-to-crush delay for the cutting green cane scenario and that for the existing situation scenario is 12.4 hours with a 95% confidence interval half width of 0.15 hours. The appoximately 4 hour extra

decrease in delays over the daily burn schedule scenario is wholly attributable to the fact that the deterioration of sugarcane only starts when the cane is cut if it is not burnt first, and therefore, the four hour delay incurred in the BurntCut stockpile in the daily burn schedule scenario is simply eliminated.

7.1.4 Farms delivering direct to the mill

The estimated mean difference between the point estimate of overall average weekly harvest-to-crush delay for the farms delivering direct to the mill scenario and that for the existing situation scenario is 3.2 hours with a 95% confidence interval half width of 0.37 hours. The main part of this saving in delays is in the lack of transloading zone delays for cane that is delivered directly to the mill. This saving is offset to some extent by the longer infield delays experienced by cane being loaded infield into road transport as can be seen from the delays in the DCutLoad and DStackLoad stockpiles in Figure 21. These delays are longer than normal infield delays because, firstly, more cane has to be accumulated to form a truck load and, secondly, loading cannot proceed until there are trucks available and road transport is not available as often as infield transport.
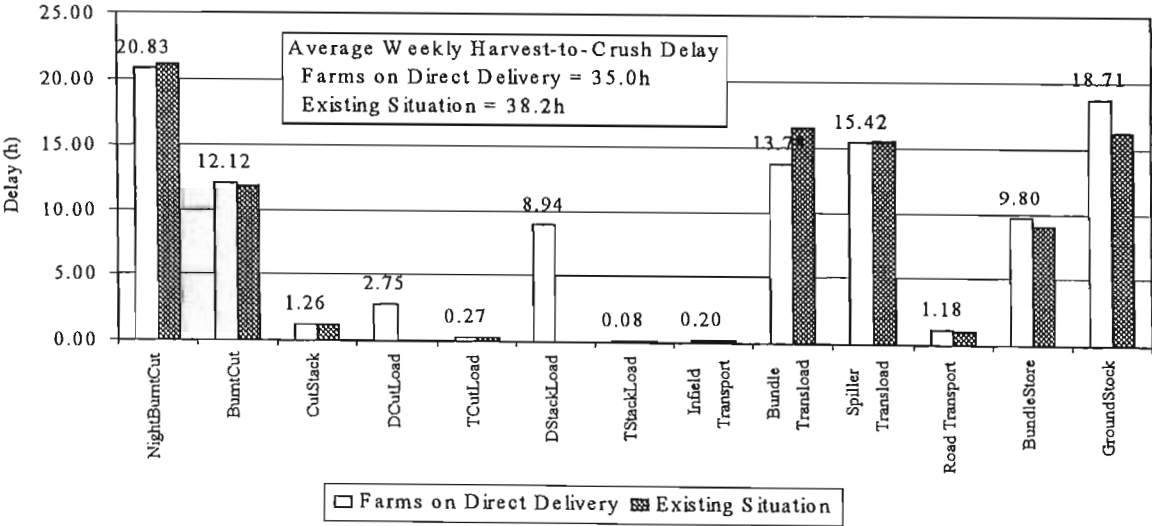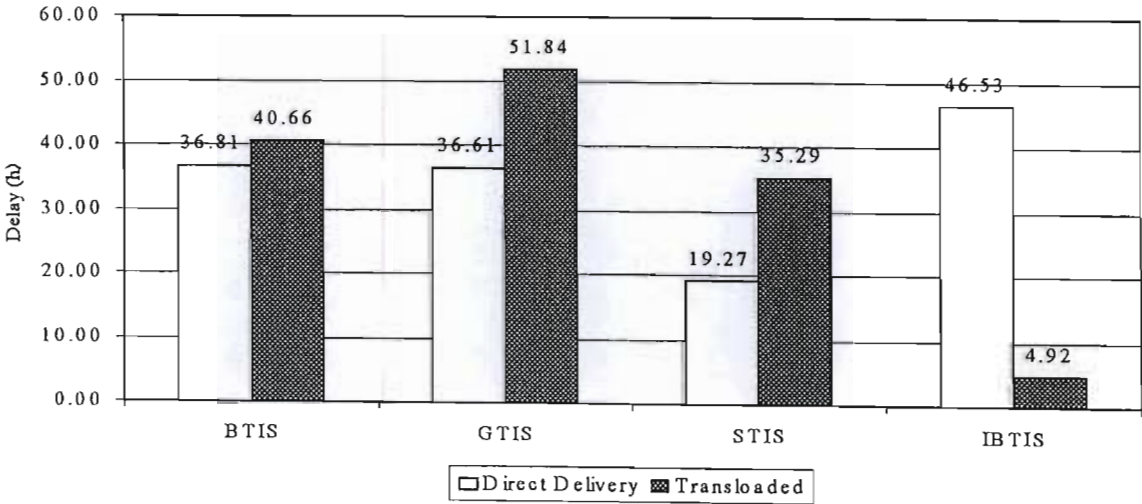

Figure 21.   Stockpile delays for farms on direct delivery scenario

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It should also be remembered that only about 34% of the tonnage delivered to the mill was able to be delivered without transloading, and this lessens the effect that the direct delivery scenario has on overall delays. In Figure 22 the point estimate of overall average weekly harvest-to-crush delays is broken down into the average weekly delays for components of cane that are transloaded or delivered directly to the mill as well as the components of cane that are offloaded by the various offloading facilities in the millyard. BTIS refers to the time in system or harvest-to-crush delay for bundle cane offloaded into the bundle stockpile. GTIS refers to loose cane offloaded into the ground stockpile by the dummy spiller. STIS refers to loose cane offloaded directly onto the mill table by the spillers. IBTIS refers to bundle cane offloaded immediately onto the mill tables to be crushed. The bundle cane offloaded directly onto the mill table constitutes a very small proportion of total tonnage crushed and therefore the delays recorded for this component of the cane are not representative. For the other offloading techniques, however, it can be seen that the delays for direct delivered cane are significantly less than those for transloaded cane, especially if the cane is delivered in loose form - the difference in delays for ground stockpiled cane and cane offloaded by spillers onto the mill tables is of the order of 15 hours. The difference is less for bundle cane because of the long delay for direct delivered stacked cane waiting to be loaded seen in Figure 21.

Figure 22. Point estimates of average weekly delays for different offloading systems in the farms on direct delivery scenario

The slightly increased delays in the millyard stockpiles illustrated in Figure 21 are due to the changes in delivery schedules necessitated by the conversion of some farms to direct delivery, which implied that there was less cane delivered to the mill on Sundays. Therefore, cane has to be stockpiled in the millyard during the week to supply the mill for crushing on Sundays. This is also illustrated in Figure 23 which shows the levels of transloading zone stockpiles and the millyard ground stockpile through the course of a three week period.
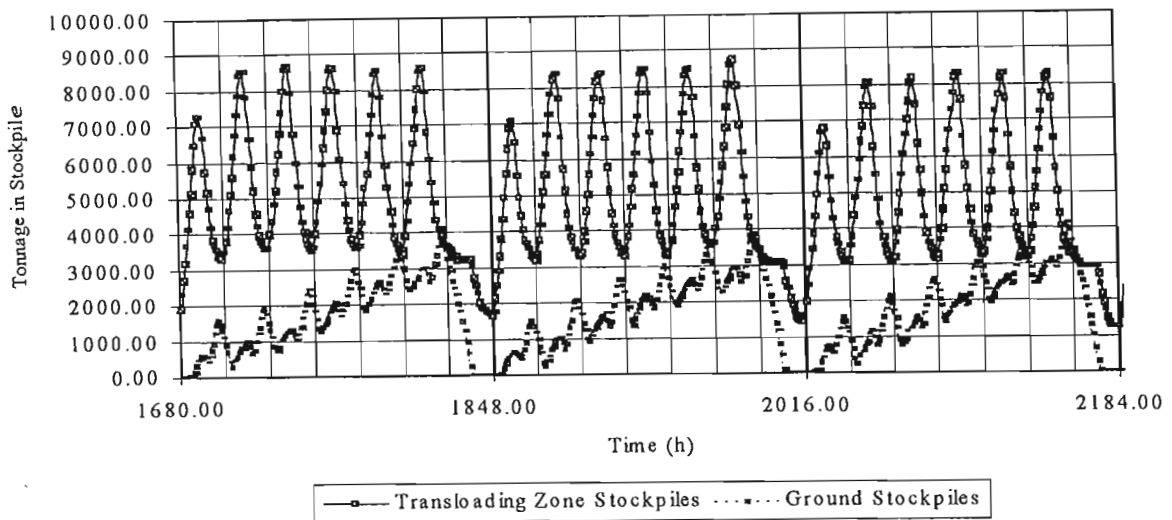
Figure 23.   Hourly average stockpile levels over a three week period for the farms on direct delivery scenario

7.1.5 Matching harvesting, delivery and milling cycles

The first scenario looked at in the investigation of matching harvesting, delivery and milling cycles was Monday to Saturday deliveries and the estimated mean difference in average weekly harvest-to-crush delays between this scenario and the existing situation scenario was 2.2 hours with a 95% confidence interval half width of 0.19 hours. This would indicate that a large proportion of the 3.2 hour decrease in delays in the farms on direct delivery scenario was attributable to the change in delivery schedule necessitated by the farms on direct delivery only being able to deliver Monday to Saturday. In Figure 24 the same pattern of transferral of delays from the transloading zones to the millyard is noted as was seen in the farms on direct delivery
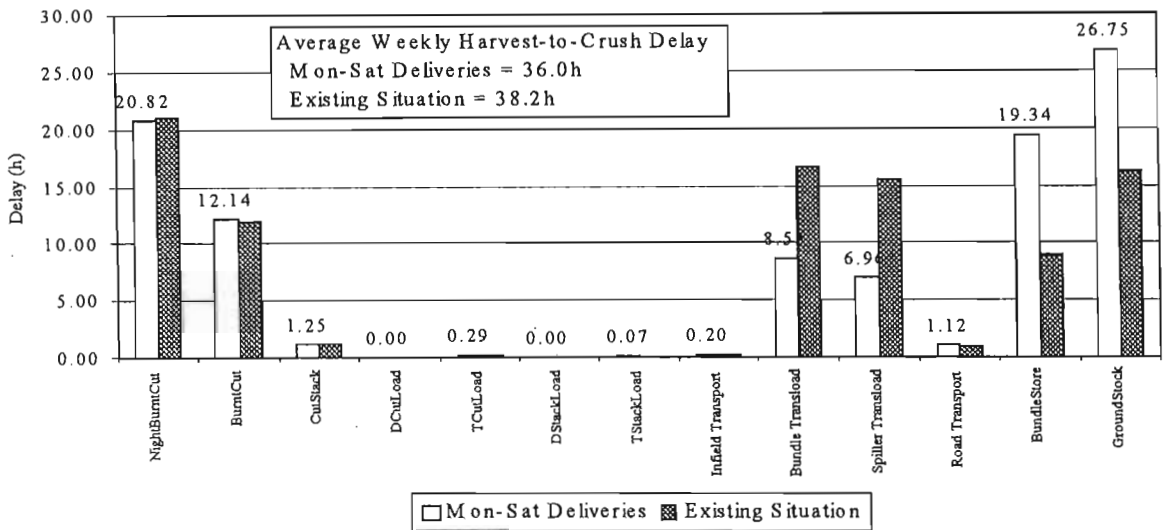
Figure 24. Stockpile delays for Monday to Saturday deliveries scenario

scenario. The effect is exaggerated because all the farms are now on Monday to Saturday deliveries and this is also reflected in the lower levels of the transloading zone stockpiles and the higher levels of the ground stockpile illustrated in Figure 25. The buildup in ground stockpile levels through the week to supply crushing on Sundays can also be seen in Figure 25.
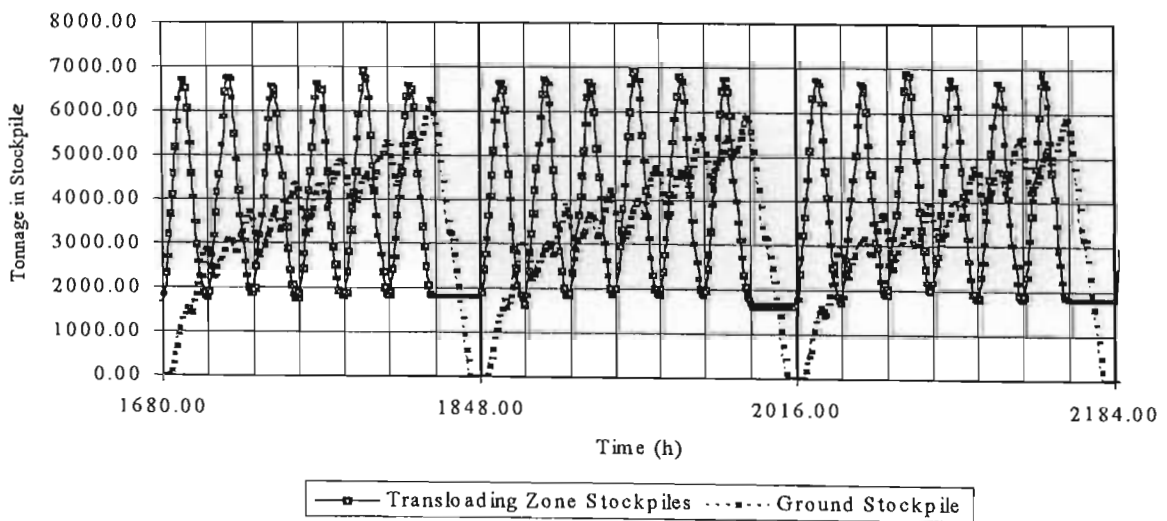
Figure 25. Hourly average stockpile levels over a three week period for the Monday to Saturday deliveries scenario

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The estimated mean difference in average weekly harvest-to-crush delays between the Monday to Sunday harvesting scenario and the existing situation scenario was 18.8 hours with a 95% confidence interval half width of 0.16 hours. This decrease in delays is due to the fact that cane does not have to be accumulated in the transloading zone and ground stockpiles to supply cane for deliveries and crushing on Sundays. It must also be noted that the daily burn schedules required for Monday to Sunday harvesting also significantly decrease harvest-to-crush delays as was demonstrated in the daily burn schedule scenario. It was assumed that Monday to Sunday harvesting would involve daily burn schedules, since none of the other existing burn schedules allowed for burnt cane to be available on a Sunday. These decreases in stockpile delays in the BurntCut, Spiller Transload, Bundle Transload, Bundle Store and Ground stockpiles are shown in Figure 26. The low stockpile levels and lack of a buildup of stockpiles through the course of the week are also illustrated in Figure 27. In Figure 28 it is apparent that for the Monday to Sunday harvesting scenario harvest-to-crush delays also do not increase through course of the week as they did in the existing situation scenario illustrated in Figure 14. This is to be expected since it has been shown in all the scenarios reported thus far how closely delays are related to stockpile levels. The only regular increases in delays are from day to night within each 24 hour period as cane harvested during the day is delivered and crushed at night.
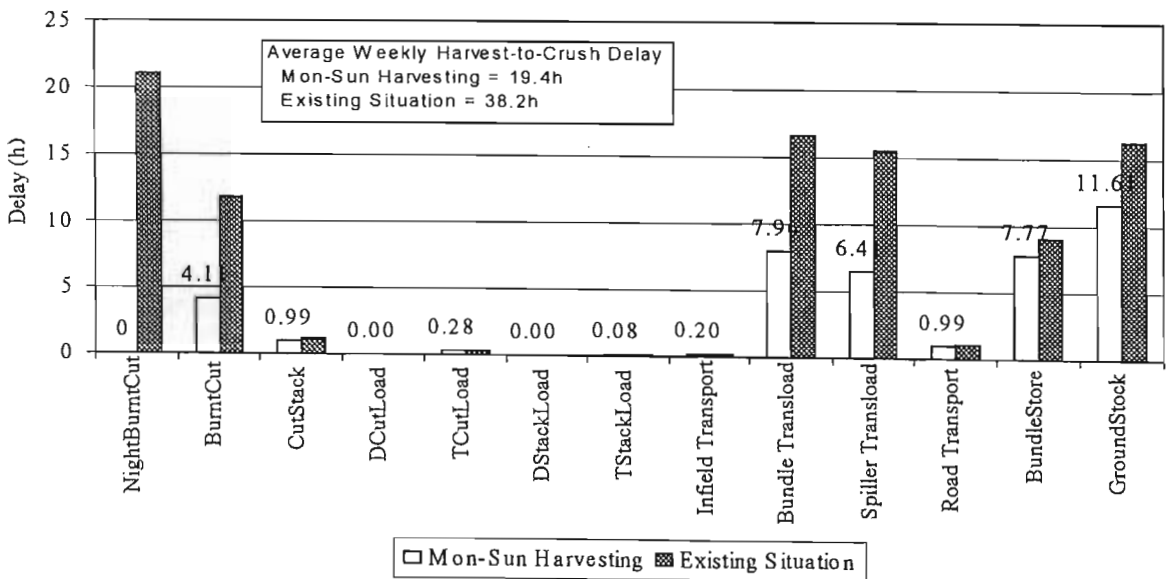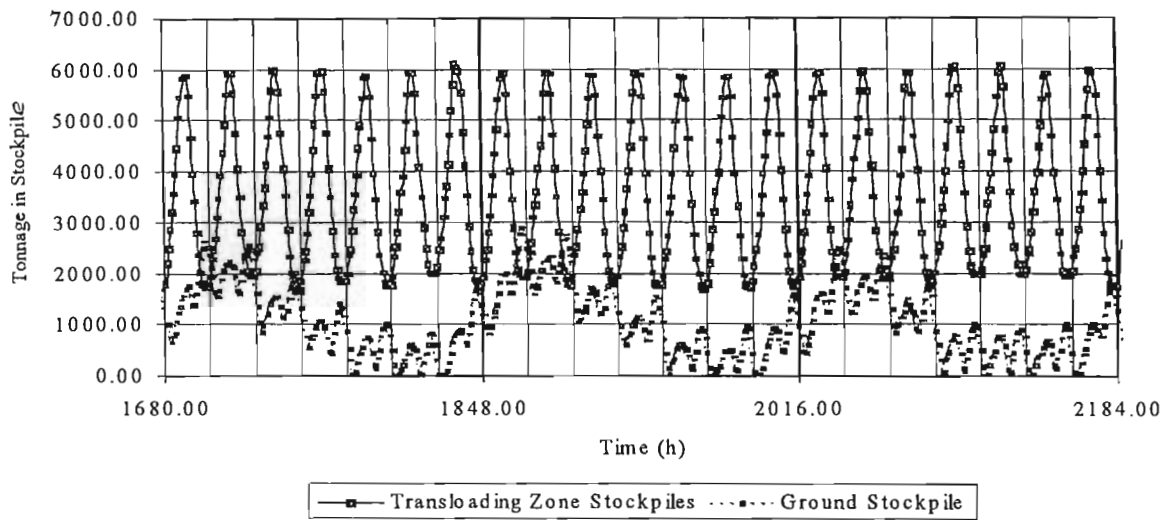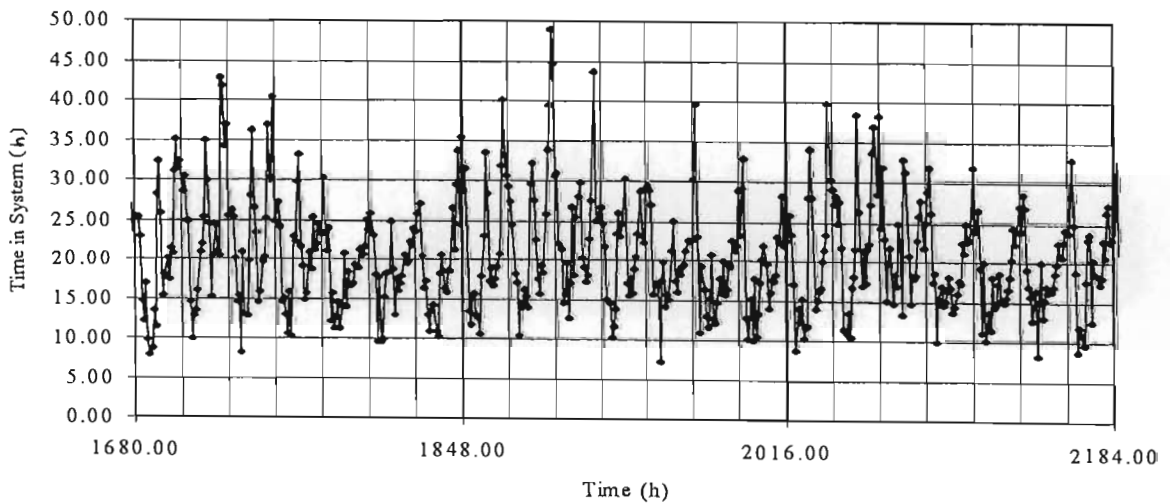

Figure 26. Stockpile delays for Monday to Sunday harvesting scenario

Figure 27. Average hourly stockpile levels over a three week period for the Monday to Sunday harvesting scenario

Figure 28. Average hourly harvest-to-crush delays over a three week period for the Monday to Sunday harvesting scenario
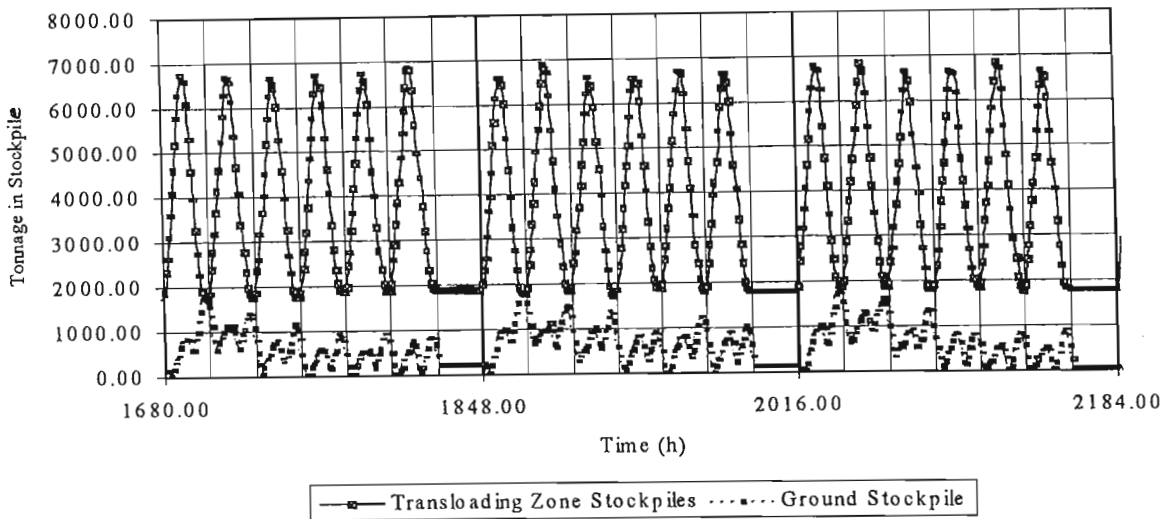
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The estimated mean difference in average weekly harvest-to-crush delays between the Monday to Saturday crushing scenario and the existing situation scenario was 10.8 hours with a 95% confidence interval half width of 0.23 hours. Once again this decrease in delays was due to the fact that there was no necessity to build up stockpiles to supply Sunday crushing, this time because the mill is not operating on Sundays. Figure 29 shows the decrease in delays in the transloading zone and millyard stockpiles where there was a build up of cane through the week in the existing situation scenario. As is indicated by the NightBurntCut and BurntCut stockpile delays, a normal burning schedule was used in this scenario and therefore, in order to be able to make comparisons between this scenario and the Monday to Sunday harvesting scenario, the scenario was rerun with a daily, mornings only burn schedule used on all farms as was necessitated in the Monday to Sunday harvesting scenario.
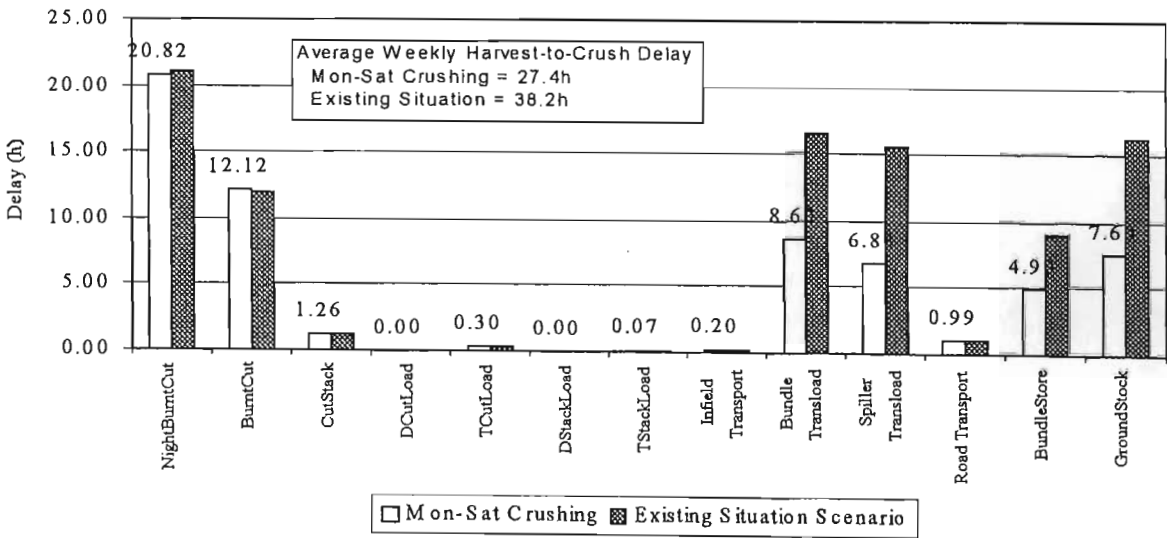
Figure 29. Stockpile delays for the Monday to Saturday crushing scenario

The estimated mean difference in average weekly harvest-to-crush delays between the Monday to Saturday crushing scenario with daily burn schedules and the existing situation scenario was 19.7 hours with a 95% confidence interval half width of 0.18 hours. This difference is comparable with the 18.8 hour estimated mean difference for the Monday to Sunday harvesting scenario and indicates that 19 hours is the approximate limit of the decrease in delays that can be achieved by matching the harvesting, delivery and milling cycles. In Figure 30 the low levels of the

transloading zone and millyard stockpiles for the Monday to Saturday crushing scenario are illustrated and it can be seen that the stockpiles remain at a constant level on Sundays, which indicates the stoppage in delivery and crushing activities on this weekday.

Figure 30. Hourly average stockpile levels over a three week period for the Monday to Saturday crushing scenario

7.1.6 Use of a single central haulier to minimise vehicle numbers

The estimated mean difference in average weekly harvest-to-crush delays between the single central haulier with 100 vehicles scenario and the existing situation scenario in which there is a total of 110 vehicles, was -1.0 hours with a 95% confidence interval half width of 0.28 hours. The estimated mean difference for the single central haulier with 80 vehicles scenario was -1.6 hours with a 95% confidence ineterval half width of 0.40 hours. Although these differences are statistically significant because the confidence intervals do not include zero, their small magnitudes indicate that reducing the number of vehicles in the system has very little effect on harvest-to-crush delays, if anything, slightly increasing the delays because cane on the transloading zones has to wait longer for vehicles to be available to transport it to the mill. When the model was run with 75 vehicles it was found that buildups occurred in the transloading zone stockpiles over the 20 week period of the run which indicated that there were not enough vehicles

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available to transport the required tonnage each week. Although reducing the number of vehicles in the system did not have an effect on harvest-to-crush delays it is notable that the model indicates that many of the vehicles in the Sezela mill area must be underutilised if the number of vehicles can be reduced by 27% and under the idealised conditions of the model, the target tonnage of cane can still be transported each week.

7.1.7 Organisation of farms into harvesting groups

The estimated mean difference in average weekly harvest-to-crush delays between the harvesting groups scenario and the existing situation scenario was 12.0 hours with a 95% confidence interval half width of 0.18 hours. The bulk of this decrease in delays is attributable to the conversion of all farms to a daily burn schedule made practically possible by the larger DRDs that the harvesting groups have to provide to the mill. This portion of the decrease in delays is similar to that found in the daily burn schedule scenario, as is shown in Figure 31. Also illustrated in Figure 31 is the slight decrease in delays in the transloading zones due to the fact that fewer farms have to incur overnight delays while waiting to accumulate a full load. The decreased ground stockpile delays are attributable to the lower levels of the tonnage in the ground stockpile for the harvesting groups scenario (925 tons average) when compared to the existing situation scenario (1457 tons average).
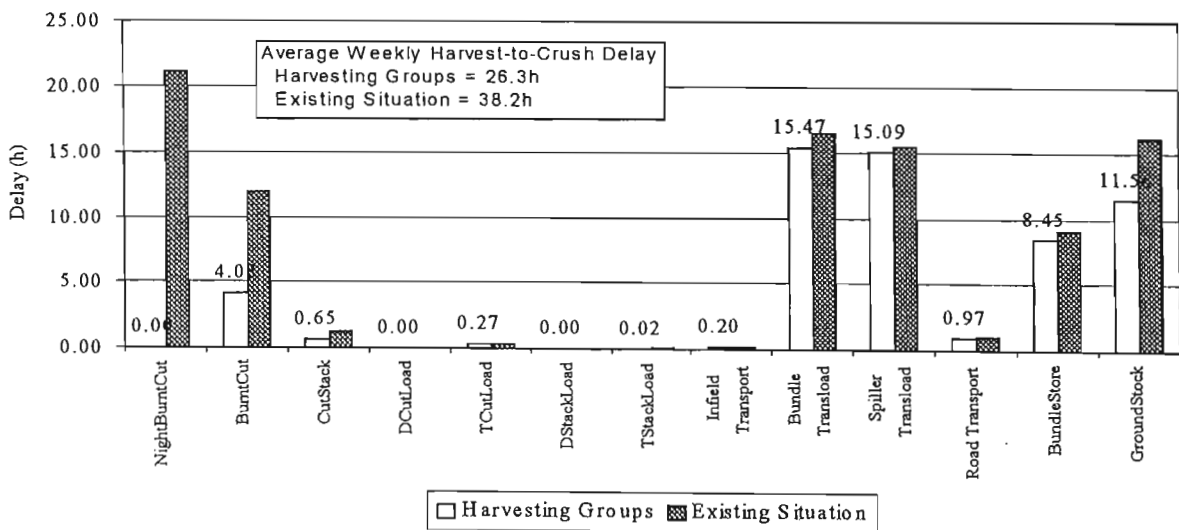

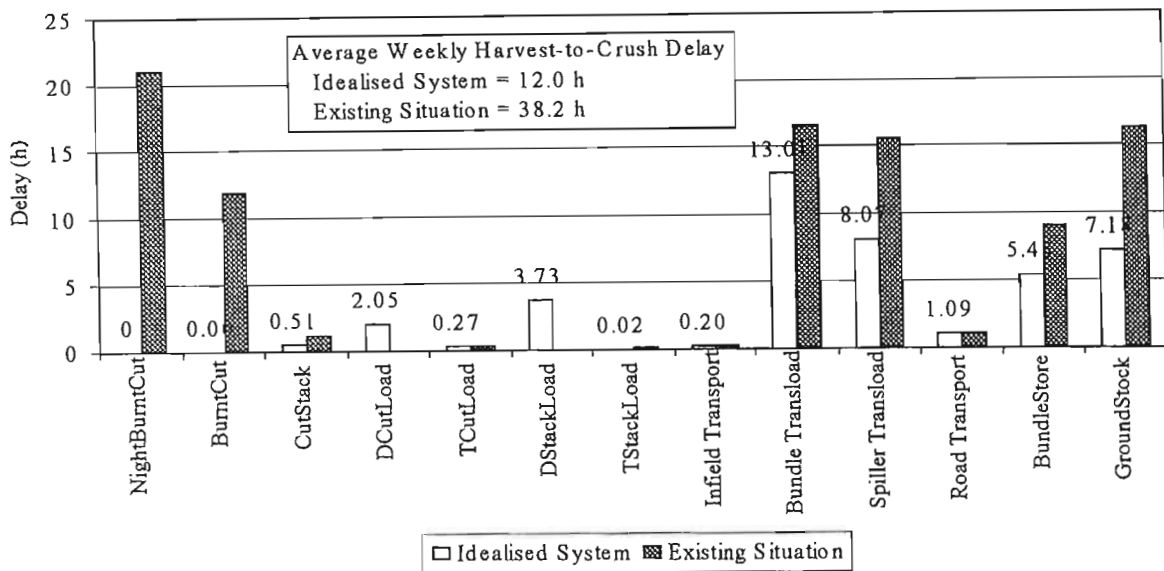**Figure 31.**   Stockpile Delays for the harvesting groups scenario

This decrease in stockpile levels was in turn caused by a slightly more balanced mill arrival distribution which was made possible by the changes in delivery schedules necessitated by the conversion of many of the farms to group harvesting. The change in mill arrivals distribution and in particular, its more balanced day-night distribution from Tuesday to Saturday is illustrated in Figure 32.
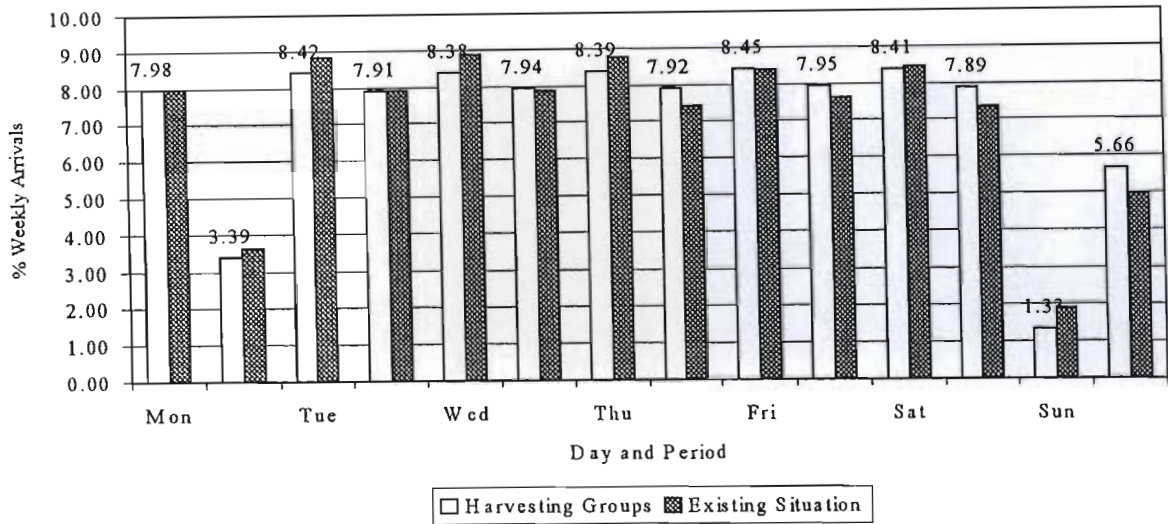
Figure 32.   Mill arrivals distribution for harvesting groups scenario

7.1.8 Idealised harvesting and delivery system

The estimated mean difference in average weekly harvest-to-crush delays between the idealised system scenario and the existing situation scenario was 26.2 hours with a 95% confidence interval half width of 0.17 hours. This decrease in delays is attributable to the combined effect of eliminating the BurntCut stockpile delays, matching harvesting, delivery and milling cycles, eliminating transloading zone delays where possible and the elimination of overnight delays incurred on farms with small DRDs that have to accumulate cane for two or more days to make a full truckload. In Figure 33 it can be seen that the major component of delays for this idealised system occurs in the transloading zones for those farms that still practise transloading, while the major component for farms that deliver direct to the mill occurs in the millyard stockpiles.

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Figure 33. Stockpile delays for the idealised system scenario

Figure 34 shows that the average weekly harvest-to-crush delay may be as low as 4.72 hours for direct delivered cane offloaded by the spillers directly onto the mill tables. Direct delivered cane stored in the bundle or ground stockpiles before being crushed incurs an average weekly delay of the order of 11.5 hours. This is approximately 7 hours greater than the delay for cane offloaded directly onto the mill tables which is same duration as is incurred in the ground stockpile. In a similar way, the delays for transloaded cane are approximately 8 hours greater than those for direct delivered cane which the duration of delays incurred in the transloading Spiller Transload stockpiles.

7.1.9 Effect of mill breakdowns

The estimated mean difference in average weekly harvest-to-crush delays between the mill breakdowns scenario and the existing situation scenario was -2.3 hours with a 95% confidence interval half width of 0.52 hours. As can be seen in Figure 35 these additional delays are mainly incurred in the millyard stockpiles. This is to be expected because of the way in which the breakdowns logic was set up in the model - most delays only affect trucks in the yard and not those on the zone.
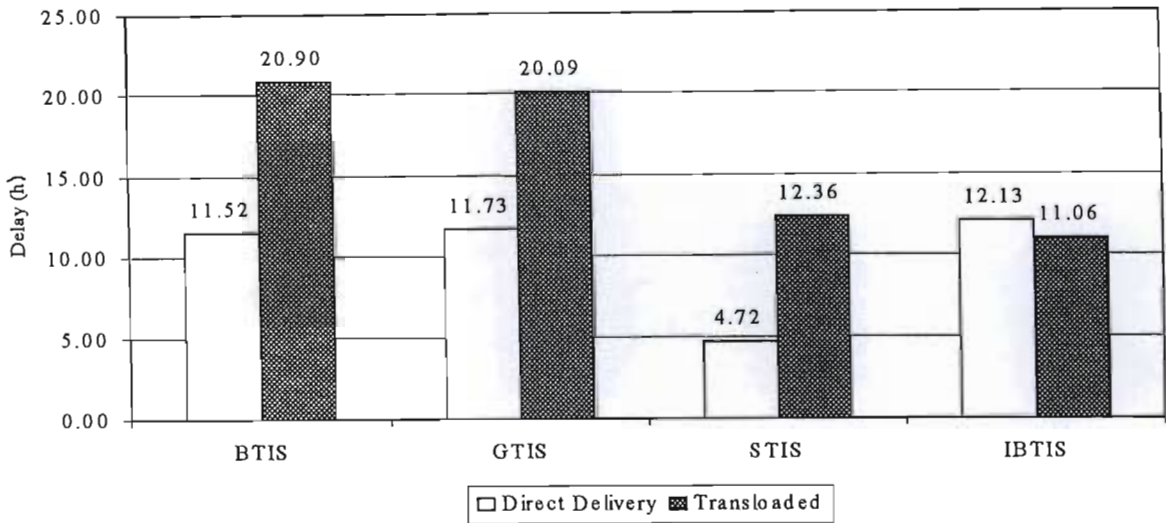
Figure 34. Point estimates of average weekly delays for different offloading systems in the idealised harvesting and delivery scenario

The average weekly total duration of all breakdowns was 5.61 hours while the average weekly total duration of breakdowns that did cause zone blockages, i.e. breakdowns that lasted longer than 45 minutes, was only 2.15 hours. Also notable about the average weekly total duration of breakdowns is that it is more than double the increase in average weekly harvest-to-crush caused by including breakdowns in the system, so the system as modelled here is not as sensitive to breakdowns as might have been expected. There is, however, a strong correlation between breakdowns and harvest-to-crush delays, as is illustrated in Figure 36. Some lag between peaks in breakdowns and peaks in delays is also evident in Figure 36. It is important to note that the breakdowns modelled in this scenario are not based on historical data from the mill. The scenario was included more to demonstrate that breakdowns could be modelled than to estimate the actual effects of breakdowns on harvest-to-crush delays.
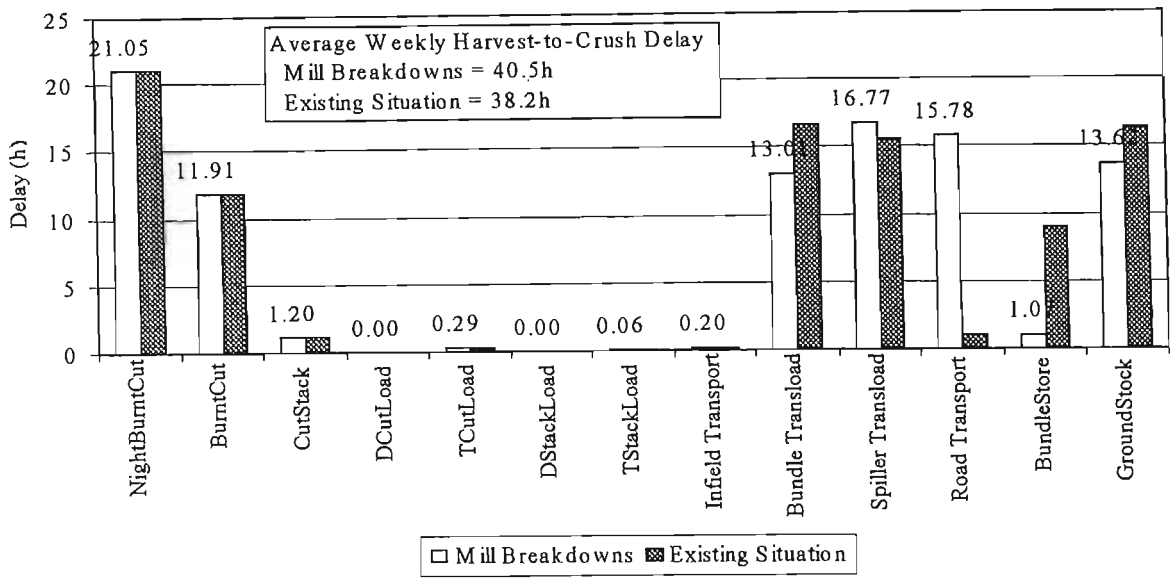
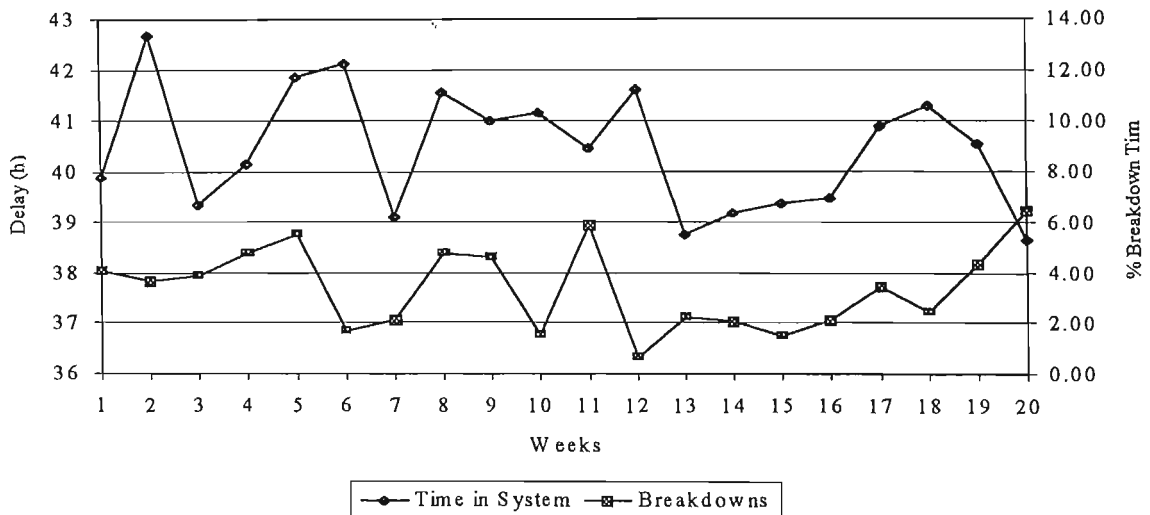**Figure 35.** Stockpile delays for mill breakdowns scenario

Figure 36. Average weekly harvest-to-crush delays and percentage mill breakdown times

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7.2 Cost Implications of Harvest-to-Crush Delays

As mentioned in the introduction, harvest-to-crush delays have cost implications because of the deterioration of cane quality caused by excessive delays. The rate of deterioration that occurs varies widely depending on numerous factors such as the ambient temperature, whether or not the cane is bundled, whether it has been burnt or not and whether it has been billeted or left as whole stalks. However, a common approximation that is used in the South African sugar industry is that the weight of sucrose in burnt, windrowed cane decreases by 1% for each additional day of delay (Lionnet, 1998; Lionnet, 1986). The figure for bundled cane is less, with a value of 0.7% commonly being used (Cox and Sahadeo, 1992). These figures do not include the decreases in recoverable sugar in the milling process caused by the non-sucrose products formed in the deterioration processes. It is very difficult to estimate the losses in the milling processes because of the many factors other than cane quality that influence the recoverable sugar ratio and it was therefore decided to use simple sucrose losses as the measure of the financial effect of harvest-to-crush delays.

Assuming for the Sezela mill area that the average sucrose content is 13%, the total tonnage produced per annum is 2 million tons and that 67% of this tonnage is stacked, the figures quoted above can be converted to loss of R1,8 million per day of harvest-to-crush delay incurred. Thus if harvest-to-crush delays in the Sezela mill area can be decreased from the average of 57 hours (measured on MCP farms) to the average of 38 hour that the model indicates is possible with the existing systems of harvesting and delivery running completely smoothly, a saving of R1,4 million per annum could be effected and if average delays could be reduced to the 12 hours indicated for the idealised harvesting and delivery system, savings of R3,4 million per annum could be made. It is more likely, however, that the actual average mill area delay could only be decreased by the 26 hours indicated in the difference between the simulated existing situation and the idealised harvesting and delivery system scenarios and this would represent a saving of R1,9 million per annum.

8. CONCLUSIONS AND RECOMMENDATIONS

A simulation model of sugarcane harvesting and delivery systems at the Sezela sugar mill was developed and used to investigate methods of reducing harvest-to-crush delays as well the effects of factors such as mill breakdowns and the number of vehicles in the system on harvest-to-crush delays. The verification and validation exercises described in Chapter 6 confirmed that the model operates reasonably and that, although the model does not account for some factors that increase real world harvest-to-crush delays, it is useful in making comparisons between different systems of sugarcane harvesting and delivery. Application of the model to the different experimental runs also described in Chapter 6 further demonstrated that the model behaves reasonably under a variety of input conditions.

The results of the experimental runs performed with the model indicated that the largest delays occur where burnt cane is waiting to be cut, in the transloading zones and in the millyard stockpiles. The delays in the stockpiles were the result of differences in harvesting, delivery and milling cycles and it was evident that the most significant decreases in harvest-to-crush delays can be brought about by matching these cycles as closely as possible. The strategies of attempting to decrease congestion at the mill by balancing the delivery plan and reducing the number of vehicles in the system had little effect on harvest-to-crush delays, although these results may have been affected by the pattern of truck arrivals at the mill within each 12-hour day or night period during the week. Changing to daily burn schedules had a marked effect on delays and was the major source of decreases in delays when individual farms were converted to harvesting groups, enabling larger areas of cane to be burnt at one time. The theoretical minimum harvest-to-crush delay that the model indicated was obtainable, was of the order of 4.7 hours, although the overall average weekly harvest-to-crush delay for an idealised harvesting and delivery system was of the order of 12 hours. This represented a 26 hour decrease in weekly average delays from the simulated existing situation scenario, bearing in mind that the values reported here represent delays that would be incurred if all components of the system are operating smoothly and all operations are performed immediately following each other within the constraints of the schedules employed in the various scenarios. This 26 hour decrease in harvest-to-crush delays probably represents a practical maximum decrease in delays from the actual average delay of 57 hours measured for MCP farms and would convert to a saving of R1,9 million per annum.

Factors other than the pattern of truck arrivals at the mill that limited the accuracy of the model's representation of the sugarcane harvesting and delivery system included the lack of overnight delays for cut cane waiting to be stacked or loaded in the fields and the assumption that direct deliveries are all transported from the fields in large trucks. The overnight delays are usually a result of the managerial discretion of the grower which is very difficult to model. The despatching and resultant patterns of arrival at the mill of trucks are also often dependent on managerial influences. These limitations will need to be addressed in any future developments of the model. Other factors that will need to be included in future developments are a mechanical harvesting subsection, which was not included in this project due to time constraints, some estimation of the effects of inclement weather and equipment breakdowns on harvesting operations and a more accurate representation of the effects of mill breakdowns, particularly of breakdowns of longer duration that necessitate the reduction of allocations.

The application of simulation modelling to the investigation of harvest-to-crush delays in the sugarcane harvesting and transport system was reasonably successful. The use of simulation modelling made it possible to model what is a complex system which would have been very difficult to realistically represent using other analytical techniques such as linear programming, scheduling algorithms or queueing theory. One drawback of the complexity of the model was the long runtime that it required. Another advantage of using simulation modelling was that all the components of the harvesting and delivery system could be integrated so that a holistic view of the system could be obtained to address the interests of both growers and millers. It also made it possible to represent the variability inherent in the system by including frequency distributions to describe different process times.

The spreadsheet data input system used to describe the harvesting and transport setups on the various farms proved to be very useful in experimenting with the different scenarios investigated in this project. It would also be useful if the model is to be applied to different mill areas. The disadvantage of the current formulation of the model in this regard is that the millyard section is specific to the Sezela mill. If the model is to be applied to other mill areas, the conversion of the millyard section of the model to a more generic framework will need to be investigated along with the other improvements already mentioned. Possibly the best way to do this would be to reformulate the model for another mill area with very different harvesting and delivery systems

and from the experience of the two projects determine how a more generic framework can be constructed. More information about the different offloading and yard management systems used at the various mills in the South African sugar industry as well as harvesting and transport systems not used in the Sezela mill area would also be required.

The methodology used in simulating the sugarcane harvesting and delivery system in this project could be adapted for other harvesting and transport systems. For example, the methodology would be very suitable for investigating queues, bottlenecks and delays that occur when trucks deliver grain to silo depots or in examining the scheduling of trucks delivering from landing zones to the mill in the timber industry as was mentioned in the literature review. The adaptation of the methodology to different harvesting and transport systems would be more difficult and time consuming than applying the model to a different sugar mill area, as the model would have to be completely reworked, but, as has been demonstrated in this project, the task would not be impossible.

Sugarcane quality is an important factor in the continued profitability of the South African sugar industry and because of the strong influence of harvest-to-crush delays on cane quality, reducing harvest-to-crush delays will be critical in ensuring the sustainability of sugarcane agriculture. Different strategies for reducing harvest-to-crush delays have been investigated with differing degrees of success. The benefits of these strategies in reducing delays and improving cane quality will have to be weighed against the costs of implementing the strategies.

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Appendix A.

Questionnaire for Farmers for Harvest-to-Crush Delay Project

Please complete the schedules applicable to you by filling in the shaded areas in the tables and the blank areas after the questions.

	Burn to Cut Delay	Cut to Despatch Delay	Transloading Zone Delays
Burnt cane	Schedule 1	Schedule2	Schedule 3
Trashed cane	Not applicable		
GROWERS WHO:			
a)Burn all their cane	Please complete schedules 1, 2 and 3		
b)Trash all their cane	Please complete schedules 2 and 3		
c) Partially burn and trash their cane	Please complete schedules 1, 2 and 3		
d) Haul cane direct to the mill (burnt)	Please complete schedules 1 and 2		
e) Haul cane direct to the mill (trashed)	Please complete schedule 2		

Please could all growers complete the appropriate General Harvesting and Transport Details section (schedule 4) questions after the two week period of the delays survey.

1.   Estate name _____
2.   Name of person completing survey _____
3.   Tons harvested 1996/97 season _____
4.   Average DRD (tons) _____
5.   Hectares under cane _____
6.   % Area burnt _____
7.   Number of cutters employed (Average for season) _____
8.   Harvesting operations days (Mon-Sat?)_____

Burn to Cut Delays

9.   No overlap means   =   *burn today and cut on the same day*
    Overlap means   =   *burn today and cut the following day*

Burning Schedule *Please mark the boxes below the day and times per week on which you generally burn your cane.*		Average Delay from Burn to Cut (hours)		% tonnage involved	
		Example (Do not fill in) No overlap burning	*Example* (Do not fill in) 1 day overlap burning	*Fill in this column* No overlap burning	*Fill in this column* 1 day overlap burning
Daily		3 hrs delay	31 hrs delay		
Three times per week	Mon; Wed; Fri	15 hrs delay	43 hrs delay		
	Tues; Thurs; Sat	19 hrs delay	47 hrs delay		
Twice per week	Mon; Thurs	27 hrs delay	55 hrs delay		
	Tues; Fri	31 hrs delay	59 hrs delay		
	Wed; Sat	35 hrs delay	63 hrs delay		
Once per week	Mon	63 hrs delay	91 hrs delay		
	Tues	67 hrs delay	95 hrs delay		
	Wed	71 hrs delay	99 hrs delay		
	Thurs	75 hrs delay	103 hrs delay		
	Fri	79 hrs delay	107 hrs delay		
	Sat	83 hrs delay	111 hrs delay		

Please complete this table from observation and use of the above guidelines.

Burn to Cut Delay		Hours
	Min	
	Avg	
	Max	

Avg Delay = (%tonnage involved on schedule 1)X(Delay for schedule 1)
      + (%tonnage involved on schedule 2)X(Delay for schedule2)
      + ...

Cut to Despatch Delays

10.

		Delay (hours)	% tonnage involved
Do you Cut, stack and haul in-------------->	Day One	3	
Do you cut and stack only in ----------------> and haul only in ---------------------------->	Day One Day Two	 30	
Do you cut, windrow (hand or machine) and haul in --->	Day One	3	
Do you cut and windrow (hand or machine) only in ---> Do you haul only in -------------------------->	Day One Day Two	 30	
do you cut and windrow (hand or machine) in --> Do you stack----------------------------------> Do you haul ---------------------------------->	Day One Day Two Day Three	 54	

Please complete this table from observation and use of the above guidelines.

Cut to Despatch Delay		Hours
	Min	
	Avg	
	Max	

Calculate Avg Delay as before.

Transloading Zone Delays

11. Please complete this 'profit' and 'loss' account.

Day zones: The schedule should be completed in the evening after the last hilo of the day OR in the morning before the arrival of the first hilo for the day.

Night zones: The schedule should be completed during the day

Please indicate if you are a;

Day Deliverer ☐   Night Deliverer ☐

24hr Deliverer ☐

Number of stacks on zone before commencement of exercise ------->				
Day	**Date**	**Stacks/trailers IN**	**Stacks/trailers OUT**	
1 M				
2 T				
3 W				
4 T				
5 F				
6 S				
7 S				
8 M				
9 T				
10 W				
11 T				
12 F				
13 S				
14 S				
Number of stacks in zone after completion of exercise --------------->				

General Harvesting and Transport System Details

12. **Equipment:**
   Please indicate the equipment on your farm.

Type of equipment	Name	2wd/4wd	Make	Number	Capacity
(a) Haulage Tractors					kW
(b) Non-Haulage Tractors					kW
(c) Trailers					tons
(d) Loaders					tons/h
(e) Cranes					tons/h
(d)Mechanical Harvester					tons/h

Burning and Cutting

13. Average area burnt at one time (ha) _____
14. Average time spent burning per day _____
15. Times of burning   Time   % of farm tonnage burnt at this time
   * Morning _____
   * Evening _____
   * Both _____
16. Percentage of cane trashed
   * Due to conditions _____
   * As standard procedure _____

17. Method of labour payment - bundle mass   _____
                                row length   _____

Output per labourer
(tons/day)

18. If stacked -   a) separate cutting and stacking operations _____
                   or   b) both done by same labourer   _____

19. No. of labourers per stack.   _____

20. Bell used to form stacks   on ground   _____
                                on trailers   _____

21. Hours spent cutting each day
   - start time   _____
   - finish time   _____

22. Percentage of cane burnt and cut on the same day   _____

23. Oldest burnt cane always cut first?   _____

24. Amount of burnt cane left at end of week   _____

Loading

25. Type of loading operation   No. of Loaders Used
   - Bell loading loose into basket trailer   _____
   - Bell loading stack trailer   _____
   - Selfloading trailers   _____
   - Other (specify)   _____

26. Hours spent loading each day:
   - start time   _____
   - finish time   _____

27. Percentage of cane cut and loaded on same day   _____

28. Oldest cut cane always loaded first?   _____

29. Amount of cut cane left at end of week   _____

Infield Transport

30. Average no. of trips completed per day   _____

Transloading

31. Offloading   **No. of Offloaders used**
   - spilt   _____
   - self-offloading   _____
   - crane offloading   _____
   - Bell offloading   _____
   - other (specify)   _____

32. Offloading into windrows   _____
                 or stacks of bundles   _____

33. Bundles split or left intact   _____

34. Adherence to First In First Out (FIFO)   _____ (%)

No. of Reloaders used

35. Reloading by crane   _____
                Bell loader   _____
                Other (specify)   _____

36. Reloading hours
      •   start time   _____
      •   finish time   _____

37. Who is your haulier   _____
38. No of trips from farm each day   _____

39. No. and capacity of private transport   _____
40. Transport shared with other farms   _____
      If yes, please name the other farm   _____

General (Optional)

41. Where do you feel the major problems are that cause Harvest-to-Crush Delays?
42. What would be the most advantageous areas to improve?
43. How much of these problems are within the control of the farmers?
44. What alterations do you make to burning system if allocation is temporarily reduced or stopped?
45. What are your feelings towards group harvesting?
46. What would you suggest to reduce Harvest-to-Crush Delays?

Loading, Offloading and Reloading Resource Elements

Resource	Resource	Resource	Resource	Resource	Resource	Resource	Resource	Resource	Resource	Resource	Resource	Resource
OffLoad1	OffLoad2	OffLoad3	OffLoad4	OffLoad5	OffLoad6	OffLoad7	OffLoad8	OffLoad9	OffLoad10	OffLoad11	OffLoad12	C

Resource	Resource	Resource	Resource	Resource	Resource	Resource	Resource	Resource	Resource	Resource	Resource	Resource
Load1	Load2	Load3	Load4	Load5	Load6	Load7	Load8	Load9	Load10	Load11	Load12	L

Resource	Resource	Resource	Resource	Resource	Resource	Resource	Resource	Resource	Resource	Resource	Resource	Resource
ReLoad1	ReLoad2	ReLoad3	ReLoad4	ReLoad5	ReLoad6	ReLoad7	ReLoad8	ReLoad9	ReLoad10	ReLoad11	ReLoad12	R

Remember to delete any extra resources in the sets element before altering the resource setup

SETUPRES.exe

Simulate

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DISCRETE

70000

CONTINUOUS

2 LEVELS
TABLESS

RATES
SPILLRATES

Transporter
GRABTRUCKS

SCHEDULES
burnsched1n
burnsched1
burnsched2n
burnsched2
burnsched3n
burnsched3
burnsched4n
burnsched4
LoadSched1
LoadSched2
LoadSched3
LoadSched4
LoadSched5
LoadSched6
LoadSched7
LoadSched8
LoadSched9
LoadSched10
LoadSched11
LoadSched12
LoadSched13
LoadSched14
LoadSched15
LoadSched16
LoadSched17
LoadSched18
LoadSched19
LoadSched20
LoadSched1000
Fieldsched1
FieldSched1000

Sets

SETS

Cutting
Stacking
Loadings
Offloading
Reloading

Sets

Farm

Transporter
GantryGrab

Expressions
BUNGANTT
BunGantryFeedT
WMAX
EMAX
DUMMAX
INTTOSPILLT
GRABMASS
GantryGrabMass
GRABLOADT
GantrySpeed
BUNMAX
bunfeedt
TABLEMAX
DELPLAN
BUNDELIV
SPILLTOCLEAN
CLEANT
SPILLCALC
DELCALC
BASKMASS
SPILLMASS
BUNQTY
BUNMASS
BBUNMASS
BundleLoadingT

Input
Variables
InitialGroundStock
InitialBunStore
StockCheckTime
StatFarmNo1
StatFarmNo2
CutTime
InfieldLoaderRate
ZoneLoaderRate
NumFarms
NumHauliers
LoadedSpeed
UnloadedSpeed
NumVehicles
DRD
BurnSched
Bundled
Transloaded
SplitBundle
AvailTrailers
Haulier
DeliveryPeriod
DeliveryDay
Distance

Model
Variables
AnimFarm1
AnimFarm2
AnimFarm3
AnimFarm4
Period
Counter1
Counter8
AvailVehicles
AvailTrailers
BundleMass
BasketMass
BundleQty
SpillerMass
TBundleQty
TSpillerMass
TruckPresent
RoadTrans
TonsToTransport
FieldLoads

Statistic
Variables
BurntCut
NightBurntCut
tonnage cut
cutstack
STACKLOAD
CUTLOAD
TRANSLOADS

Millyard
Variables
Ratio
DESTVAR
WEEKLYTARGET
ITIN
TESTER
BUNSTORE
groundstock
DUMMYTABLE
DAYFLAG
TrackFlag
Weekday

Statics
WEYINT
HOOKUPT
SPILL
UNHOOKT
MOVETT
WEYOUTT

RESOURCES
Repeat(Cut,100)
Repeat(Stack,100)
BUNGANTRY

DISTANCES
GRABTRUCKS_Dst
GantryGrab_Dst

Read in farm and haulier data from spreadsheets

Create → Read → VBA
        Farm Data1
                    → Dispose
Create → Read → Assign
0.00000001 Farm Data Counter1
Create → Read → Assign
0.00000001 Hauliers
AvailVehicles
TAvailVehicles
Counter8

Day-night and weekday variables

Create → Delay → Choose
12   0.00001
Create
24
Create → Assign
4   TESTER
Create → ASSIGN
          SPILLRATES(1)
          SPILLRATES(2)

→ Dispose

→ ASSIGN
   SPILLRATES(2)

If spillrates(1)==0.AND.spillrates(2)==0
If (SPILLRATES(1)==0).AND.(SPILLRATES(2).NE.0)
If (SPILLRATES(1).NE.0).AND.(SPILLRATES(2)==0)
Else

→ ASSIGN → Dispose
   SPILLRATES(1)

→ ASSIGN
   SPILLRATES(1)
   SPILLRATES(2)

Figure B-2. Arena model flowchart of burning and trashcutting processes

Burning and Trashcutting Processes

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Stacking Process

Station Farm → **BRANCH**
If BUNDLED(FarmNum,1)==1
If SplitBundle(FarmNum,1)==1
Else

Assign
Tcutstack
cutstack
→ **GROUP**
FarmNum
BundleMass(FarmNum,1)
→ **Assign**
MASS
Stacked
bundmassA
→ **Signal**
FarmNum
→ **Process**
Stacking
→ **Tally**
T in CutStack
→ **Assign**
Stack Time
Tcutstack
cutstack
Tstackload
STACKLOAD
FieldLoads

Assign
Tcutload
CUTLOAD
FieldLoads
MASS

BundleMass variable logic

Create → **BRANCH**
If BUNDLED(FarmNum,1)==1
If SplitBundle(FarmNum,1)==1
Else

Assign
BundleMass
→ **Wait**
FarmNum

Assign
BundleMass
→ **Wait**
FarmNum

Dispose

Figure B-4. Arena model flowchart for loading processes

Loading Processes

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Create → Choose → Assign (BundleQty) → Wait (FarmNum+2000)

If (Transloaded(FarmNum,1)==0).AND.(Bundled(FarmNum,1)==1)
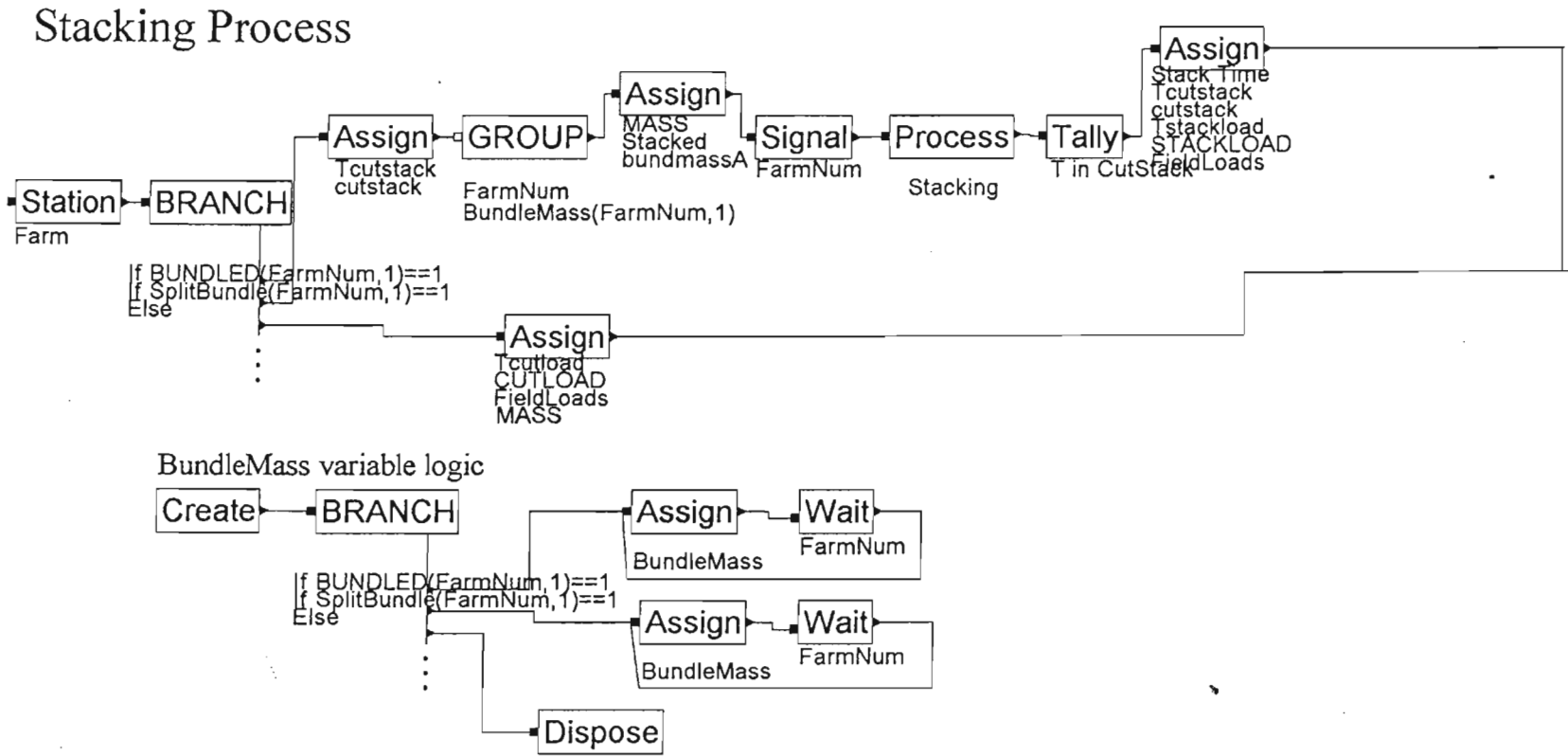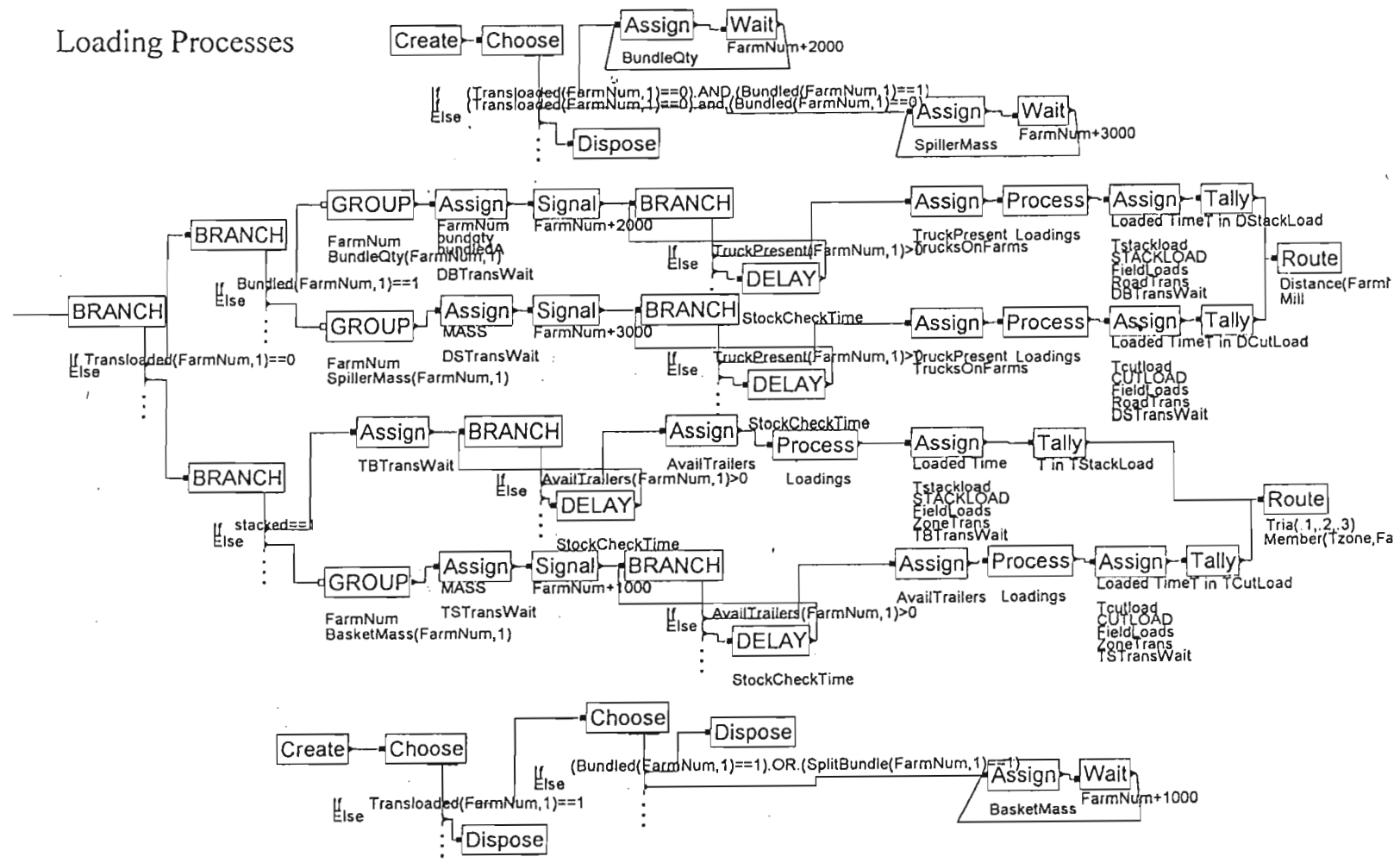(Transloaded(FarmNum,1)==0).and.(Bundled(FarmNum,1)==0) → Assign (SpillerMass) → Wait (FarmNum+3000)
Else → Dispose

BRANCH
If Transloaded(FarmNum,1)==0
Else

BRANCH
If Bundled(FarmNum,1)==1
Else

GROUP (FarmNum BundleQty BundleQty(FarmNum,1)) → Assign (FarmNum bundqty bundledA DBTransWait) → Signal (FarmNum+2000) → BRANCH

GROUP (FarmNum SpillerMass(FarmNum,1)) → Assign (MASS DSTransWait) → Signal (FarmNum+3000) → BRANCH StockCheckTime

If TruckPresent(FarmNum,1)>DrucksOnFarms
Else → DELAY
→ Assign (TruckPresent Loadings) → Process (Tstackload STACKLOAD FieldLoads RoadTrans DBTransWait) → Assign (Loaded TimeT in DStackLoad) → Tally → Route (Distance(FarmMill))

If TruckPresent(FarmNum,1)>DruckPresent Loadings TrucksOnFarms
Else → DELAY
→ Assign → Process (Tcutload CUTLOAD FieldLoads RoadTrans DSTransWait) → Assign (Loaded TimeT in DCutLoad) → Tally

BRANCH
If stacked==1
Else

Assign (TBTransWait) → BRANCH
If AvailTrailers(FarmNum,1)>0
Else → DELAY (StockCheckTime)
→ Assign (AvailTrailers Loadings) → Process (Tstackload STACKLOAD FieldLoads ZoneTrans TBTransWait) → Assign (Loaded Time T in TStackLoad) → Tally → Route (Tria(.1,.2,.3) Member(Tzone,Fa))

GROUP (FarmNum BasketMass(FarmNum,1)) → Assign (MASS TSTransWait) → Signal (FarmNum+1000) → BRANCH StockCheckTime
If AvailTrailers(FarmNum,1)>0
Else → DELAY (StockCheckTime)
→ Assign (AvailTrailers Loadings) → Process (Tcutload CUTLOAD FieldLoads ZoneTrans TSTransWait) → Assign (Loaded TimeT in TCutLoad) → Tally

Create → Choose
If Transloaded(FarmNum,1)==1
Else → Dispose

Choose → Dispose
If (Bundled(FarmNum,1)==1).OR.(SplitBundle(FarmNum,1)==1)
Else → Assign (BasketMass) → Wait (FarmNum+1000)
Dispose

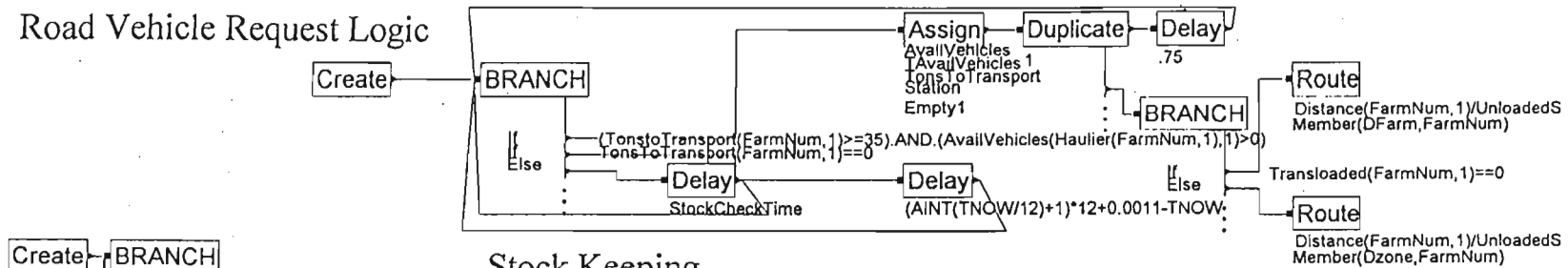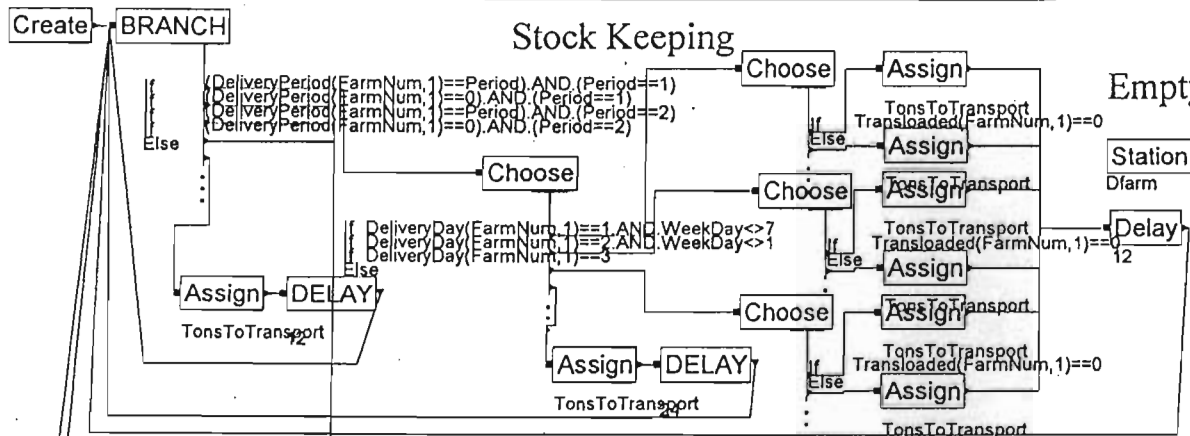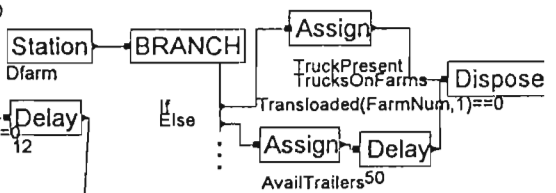**Figure B-5.** Arena model flowchart for transloading processes

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Figure B-6. Arena model flowchart for vehicle availability logic

Figure B-7. Arena model flowchart for millgate processes

WEIGHBRIDGE AND ROUTING DECISION

Mill Gate

Station — Tally — Count — Chance — Assign — Store — Choose — Seize — Signal — Delay — Choose — Assign — Release — Leave
Mill — MillArrivals/SezelaIn_C — test — weyinstore — WEYBIN — 200000 — WEYINT — DEST/TTIN/BundlePic — WEYBIN

With3
Else

Seize
WEYBIN

If BundledA>=1
Haulier(FarmNum,1)==32
Else

Seize
WEYBIN

If bundledA.AND.TTIN(4)<2
If BundledA==0.AND.TEST==1.AND.TTIN(TESTER)<EMAX.AND.TTIN
If BundledA==0.AND.TTIN(1)<EMAX.AND.TTIN(1)<=TTIN(2)
If BundledA==0.AND.TTIN(2)<WMAX
If BundledA==0.AND.TTIN(3)<DUMMAX
Else

Assign DEST/TTIN/TestPic
Assign DEST/TTIN — Release — Leave WEYBIN
Assign DEST/TTIN
Assign DEST/TTIN

Count — Delay
NOTNEEDED/StockCheckTime

Station — Tally — Count — Route
INTERIM1 — Time in Road Transport/YardIn_C — INTTOSPILLT(DEST)
OFFLOADINGS(DEST)

Create — Assign — Wait
UnitransPriority/HaulierPriority — 200000

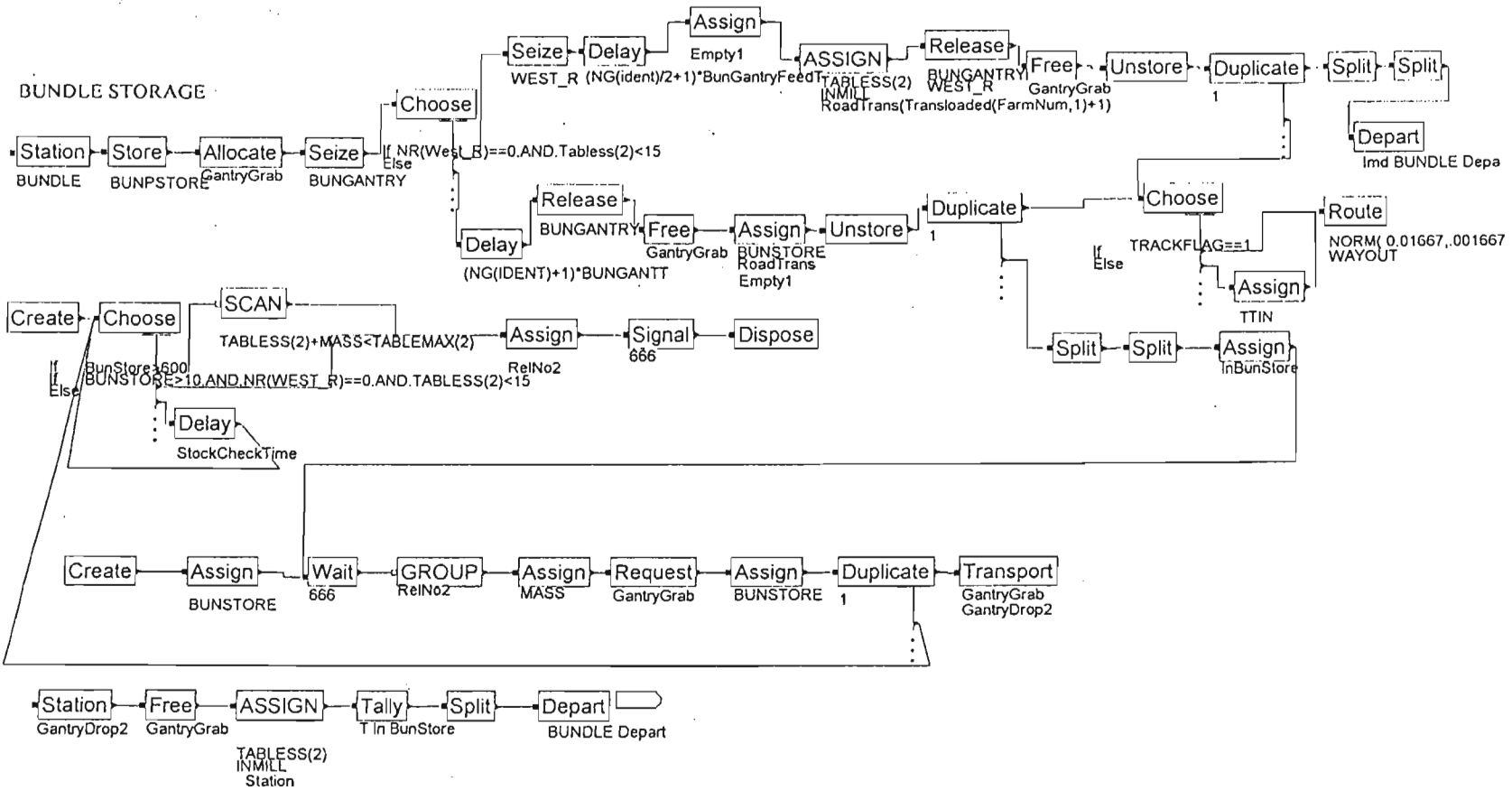Figure B-8.   Arena model flowchart for spiller processes

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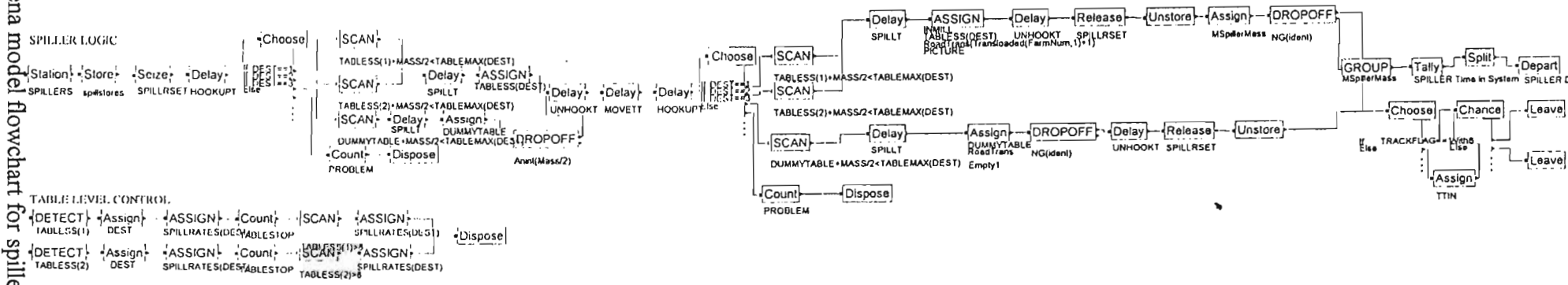
Figure B-9. Arena model flowchart for bundle offloading and storage processes
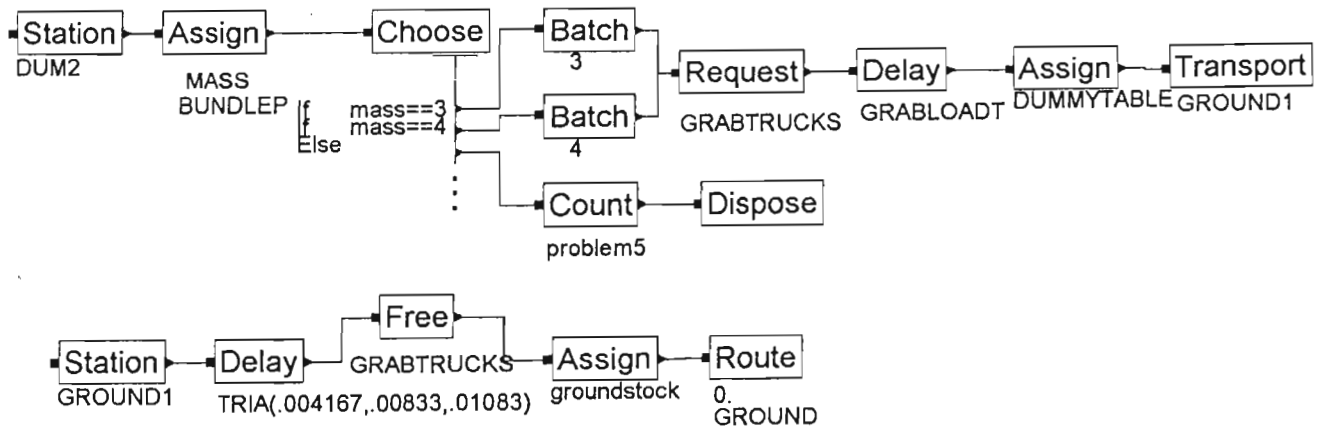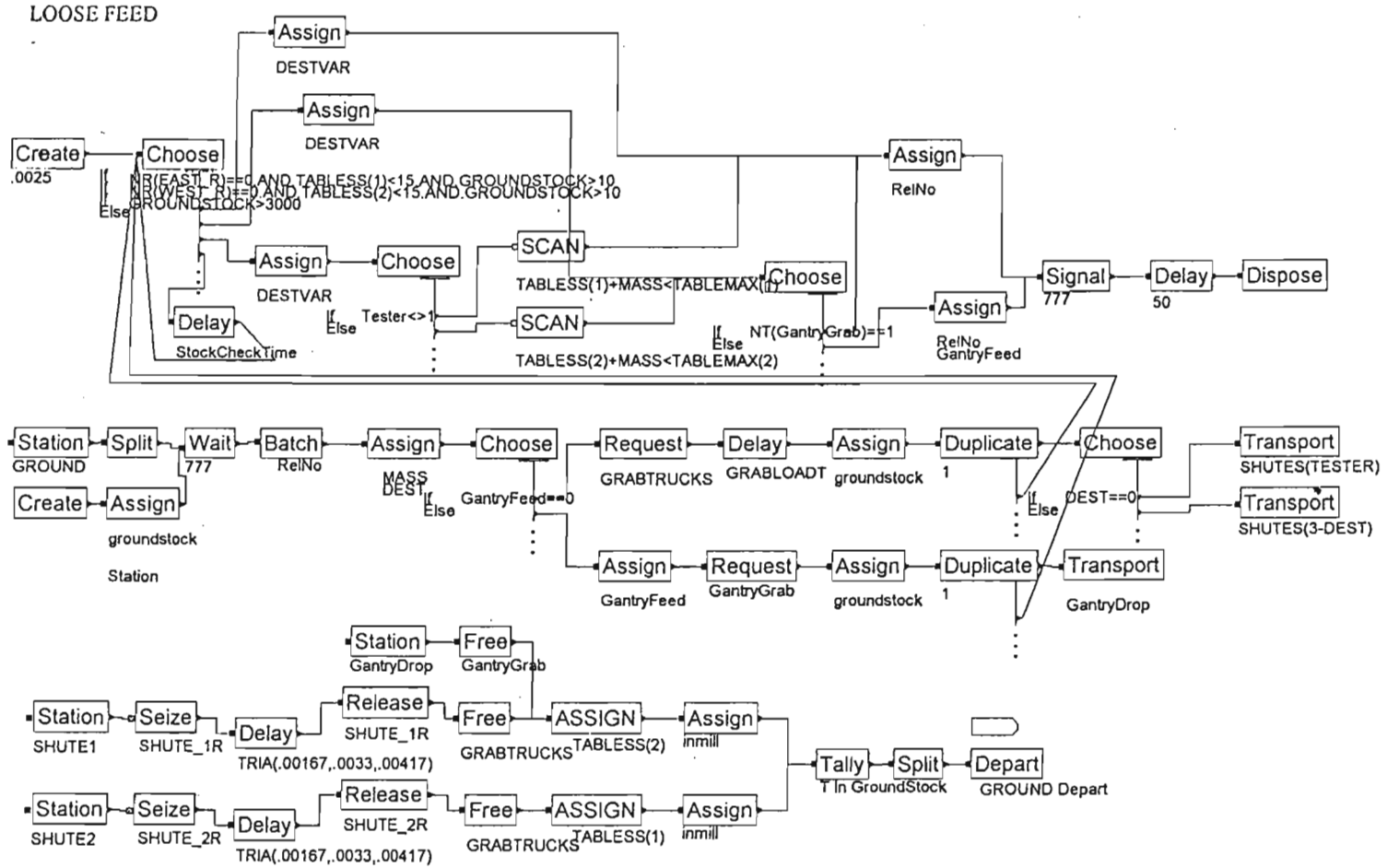
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Figure B-10. Arena model flowchart for the dummy spiller area clearing process

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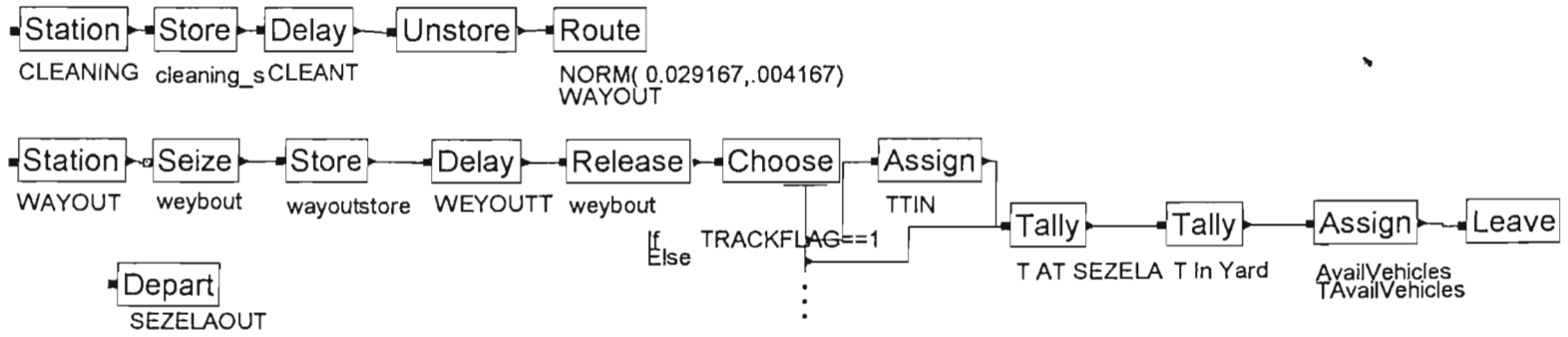**Figure B-11.** Arena model flowchart for loose feed processes

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Figure B-12. Arena model flowchart for cleaning and weighing out processes

WEIGHBRIDGE OUT

■Station■→■Store■→Delay■→—Unstore■→—Route
CLEANING cleaning_s CLEANT   NORM(0.029167,.004167)
                                       WAYOUT

■Station■→□Seize■→■Store■→Delay■→—Release■→Choose■→—Assign
WAYOUT   weybout   wayoutstore WEYOUTT weybout   TTIN
                                            If   TRACKFLAG==1
                                            Else

■Depart
SEZELAOUT

Tally■→■Tally■→■Assign■→—Leave
T AT SEZELA T In Yard AvailVehicles
                       TAvailVehicles

Appendix C. Arena summary output example

Beginning replication 21 of 21

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ARENA Simulation Results
N . LECLER - License #9710487

Summary for Replication 21 of 21

</div>

Project: Run execution date : 10/22/1998
Analyst: Model revision date: 10/21/1998

Replication ended at time   : 3528.0
Statistics were cleared at time: 3360.0
Statistics accumulated for time: 168.0

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TALLY VARIABLES

</div>

Identifier	Average	Half Width	Minimum	Maximum	Observations
Imd BUNDLE Time in Sys	48.398	(Corr)	15.107	120.08	525
T in NightBurntCut	20.808	(Corr)	12.023	67.966	3762
T In BunStore	4.6915	(Corr)	.12501	14.754	461
T in TStackLoad	.08192	(Corr)	9.3186E-07	35.735	8248
T in DCutLoad	--	--	--	--	0
MillArrivals	.07546	.01321	3.5135E-05	5.7912	2178
T In GroundStock	5.4683	.52482	.11998	18.561	3417
GROUND Time in System	39.874	6.8063	3.2313	1259.3	12967
SPILLER Time in System	40.278	(Corr)	2.1931	921.25	1595
Time in Road Transport	.96955	(Corr)	.20854	3.5056	2179
T In Yard	.33046	.00632	.14314	.83022	2179
BUNDLE Time in System	36.925	(Corr)	3.8886	164.08	3562
T in DStackLoad	--	--	--	--	0
T AT SEZELA	.42403	.02737	.19185	1.3214	2179
T in Spiller Transload	19.543	(Corr)	.69585	1123.4	2044
T in CutStack	1.2393	.29724	.09140	39.773	8244
T in BurntCut	12.100	(Corr)	.02150	55.831	59692
T in Infield Transport	.19963	7.2413E-04	.10089	.29873	11690
T in TCutLoad	3.4019	.86461	.18182	794.58	3442
T in Bundle Transloads	16.082	(Insuf)	.54306	130.08	135

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DISCRETE-CHANGE VARIABLES

</div>

Identifier	Average	Half Width	Minimum	Maximum	Final Value
NR(OFFLOADING(STATFARM	.03999	.02154	.00000	2.0000	.00000
NR(BUNGANTRY)	.28655	(Insuf)	.00000	1.0000	.00000
TTIN(2)	1.6801	(Corr)	.00000	3.0000	.00000
TONSTOTRANSPORT(STATFA	22.571	(Insuf)	.00000	221.18	7.0000
TCUTLOAD	512.12	22.288	453.00	635.00	480.00
TTIN(1)	1.8091	(Corr)	.00000	3.0000	.00000
TONSTOTRANSPORT(STATFA	52.414	(Insuf)	.00000	352.01	7.0000
NR(WEST_R)	.35988	.03937	.00000	1.0000	.00000
PERIOD	1.5000	(Insuf)	1.0000	2.0000	1.0000
AVAILVEHICLES(19,1)	2.3336	(Insuf)	.00000	4.0000	4.0000
TTONNAGE CUT	1.3075E+06	(Corr)	1.2684E+06	1.3318E+06	1.3318E+06
AVAILVEHICLES(HAULIER(	15.859	3.6892	.00000	36.000	33.000
BUNDLE STORE	102.16	21.077	3.0000	296.00	5.0000
TSTACKLOAD	17.832	3.6831	.00000	55.000	23.000
NR(DUMMY_R)	.20093	.04846	.00000	1.0000	.00000
TRANSLOADS(STATFARMNO2	256.91	(Insuf)	5.0000	416.00	14.000
TRUCKPRESENT(STATFARMN	.00153	(Insuf)	.00000	1.0000	.00000
AVAILVEHICLES(HAULIER(	15.859	3.6892	.00000	36.000	33.000
ZONETRANS	89.863	41.372	.00000	318.00	5.0000
GRABTRUCKS 1 Idle	.43113	(Corr)	.00000	1.0000	1.0000
TRANSLOADS(STATFARMNO1	424.21	(Corr)	5.0000	668.00	5.0000
TRUCKPRESENT(STATFARMN	.00286	(Insuf)	.00000	1.0000	.00000

GRABTRUCKS 2 Idle	.44088	(Corr)	.00000	1.0000	.00000
GRABTRUCKS 1 Busy	.52986	(Corr)	.00000	1.0000	.00000
NR(RELOADING(STATFARMN	.32568	(Insuf)	.00000	1.0000	.00000
TRUCKSONZONES	10.146	4.5988	2.0000	40.000	4.0000
GRABTRUCKS 2 Busy	.53517	(Corr)	.00000	1.0000	.00000
GRABTRUCKS 1 Inactive	.03901	(Insuf)	.00000	1.0000	.00000
GRABTRUCKS 2 Inactive	.02395	(Insuf)	.00000	1.0000	1.0000
NR(SHUTE_1R)	.01387	.00397	.00000	1.0000	.00000
GROUNDSTOCK	422.18	114.89	4.0000	1152.0	5.0000
TSTRANSWAIT	459.37	20.988	401.00	593.00	431.00
WEEKDAY	4.0000	(Insuf)	1.0000	7.0000	1.0000
NR(SHUTE_2R)	.04389	.01010	.00000	1.0000	.00000
AVAILTRAILERS(STATFARM	2.1697	.45858	.00000	3.0000	3.0000
TBTRANSWAIT	17.832	3.6831	.00000	55.000	23.000
TCUTSTACK	447.75	97.005	149.00	1016.0	149.00
NR(EAST_R)	.40336	(Corr)	.00000	1.0000	.00000
TRANSLOADS(19,1)	24.100	(Insuf)	.00000	36.000	36.000
CUTLOAD(STATFARMNO2,1)	4.6697	1.3529	.00000	13.000	3.0000
AVAILTRAILERS(STATFARM	2.7057	.70848	.00000	4.0000	4.0000
NR(LOADINGS(STATFARMNO	.51245	.28896	.00000	3.0000	.00000
TAVAILVEHICLES	62.522	10.269	16.000	106.00	105.00
Dummy Spiller Table	6.8689	.94752	~0.5000	35.500	1.0000
TONSTOTRANSPORT(19,1)	11.922	(Insuf)	.00000	64.350	.00000
STACKLOAD(STATFARMNO2,	.00000	(Insuf)	.00000	.00000	.00000
CUTLOAD(STATFARMNO1,1)	6.8388	2.0867	.00000	27.000	4.0000
TTRANSLOADS	9019.5	961.25	3799.0	13306.	3910.0
STACKLOAD(STATFARMNO1,	.00000	(Insuf)	.00000	.00000	.00000
DSTRANSWAIT	.00000	(Insuf)	.00000	.00000	.00000
DBTRANSWAIT	.00000	(Insuf)	.00000	.00000	.00000
TRUCKSONFARMS	.00000	(Insuf)	.00000	.00000	.00000
West Spiller Table	27.555	3.3732	-0.0666	76.613	-0.0222
STRANSWAIT	7526.6	907.31	2521.0	11340.	2657.0
BTRANSWAIT	332.15	(Insuf)	.00000	770.00	90.000
MillRoadTrans	410.86	64.998	.00000	1187.0	.00000
GRABTRUCKS Active	1.9370	(Insuf)	1.0000	2.0000	1.0000
TRUCKPRESENT(19,1)	.05441	(Insuf)	.00000	1.0000	.00000
East Spiller Table	23.667	2.9922	-0.0395	53.651	-0.0313
DirectRoadTrans	.00000	(Insuf)	.00000	.00000	.00000
GantryGrab Busy	.34392	.04580	.00000	1.0000	.00000
GRABTRUCKS Busy	1.0654	(Corr)	.00000	2.0000	.00000
TTIN(3)	.99008	.24117	.00000	3.0000	.00000

COUNTERS

Identifier	Count	Limit
Burn1	25396	Infinite
Burn2	26384	Infinite
WESTSTOP	83	Infinite
Burn3	7912	Infinite
PROBLEM	0	Infinite
NOTNEEDED	1289	Infinite
Burn4	0	Infinite
YardIn_C	2179	Infinite
SezelaIn_C	2179	Infinite
problem5	0	Infinite
BUNDLE Depart_C	3562	Infinite
Burn4n	0	Infinite
EASTSTOP	107	Infinite
Imd BUNDLE Depart_C	525	Infinite
Burn3n	0	Infinite
Prob1	242	Infinite
Burn2n	1170	Infinite
Burn1n	2592	Infinite
SPILLER Depart_C	46321	Infinite
Trash5	0	Infinite
SEZELAOUT_C	2179	Infinite
GROUND Depart_C	12967	Infinite

OUTPUTS

Identifier	Value
TAVG(IMD BUNDLE TIME I	48.398
TAVG(SPILLER TIME IN S	40.278
TAVG(GROUND TIME IN SY	39.874
TAVG(BUNDLE TIME IN SY	36.925

ARENA Simulation Results
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Output Summary for 21 Replications

Project: Run execution date : 10/22/1998
Analyst: Model revision date: 10/21/1998

OUTPUTS

Identifier	Average	Half-width	Minimum	Maximum	# Replications
TAVG(IMD BUNDLE TIME I	43.838	2.9717	29.536	55.944	21
TAVG(SPILLER TIME IN S	37.968	1.7428	33.026	50.895	21
TAVG(GROUND TIME IN SY	39.050	1.2649	33.988	46.266	21
TAVG(BUNDLE TIME IN SY	38.395	.64452	36.409	41.975	21

Simulation run time: 986.33 minutes.
Simulation run complete.