Introduction

The sugar producing areas of Australia are scattered along the eastern coast from Mossman (16°S) in north Queensland to Yamba (29°S) in New South Wales, a distance of 2100 kilometers. In 1996, Australia produced about 40 Mt of cane and from this made over 5 Mt of sugar. With a domestic market of around 920,000 t, by far the major share of this production is therefore destined for export. Thus the focus of Australia's 6800 cane farmers is on world price. This introduces a very strong element of international competitiveness into the Australian industry.

All sugar cane grown in Australia is harvested mechanically by self-propelled harvesting machines. Australia pioneered mechanical cane harvesters and achieved 100 % conversion to mechanical harvesting in 1979. Today, Australia is a world leader in mechanised harvesting and the efficient transport of cane from the field to the mill. Largely, as a result of this, the Australian sugar industry has been able to expand significantly over the past few decades while remaining internationally competitive. Maintaining this position, however, requires continual development and ongoing improvement. (SRDC, 1999)

Sugar cane must be milled as soon as possible, and within 16 hours of harvesting, to minimise deterioration. For this reason it is important that the cane farms are in close proximity to the sugar mills they supply.

Mill owners have made a substantial capital investment in cane railway networks and rolling stock. To ensure the prompt delivery of cane to the mills, Australian mills (23 mills) own and operate a network of 4,190 kilometers of narrow-gauge cane railways. This railway network forms the third largest rail transport system in Australia.

In the 1996 season, 95% of the record cane crop was transported to sugar mills using railways. Six mills in Australia use road transport systems exclusively, and several use a combination of road and rail transport. (Keating and Wilson, 1997)

Place of cane harvesting and transport in the manufacturing of raw sugar

Transporting cane from the field to the mill is an expensive process. Both capital and operating costs are large. Cane transport is the largest cost unit in the manufacturing of raw sugar accounting for about one third of the total manufacturing costs.

In Australia cane transport is undertaken by the supplier and the factory together. As a rule, the supplier is responsible for loading the cane into a factory-supplied container (bin) and moving the container to a specified delivery point near to (or in) his field. From this point the factory is responsible for the transport of the cane to the factory and for weighing the cane and recording its delivery before it is crushed. The factory is also responsible for the supply of empty containers to the delivery point.

Cane railway transport system - previous research

Cane railway systems perform two major tasks. Firstly, they take empty bins from the mill and deliver them to the growers where they are filled with chopped cane, and secondly, they collect the full bins from the growers and return them to the mill. At the mill, the full bins are weighed and then move onto a tip where the cane is removed. The now empty bins are ready for delivery to the growers.

Sugar Research Institute (SRI), Mackay began investigating the scheduling of cane railway transport in the mid-1960s. For these initial applications, the schedules were generated and checked manually. By 1972, SRI had developed a computer-aided scheduling system, CASCHD (Shepherd and James, 1972). This system used input describing the layout of the cane railway system, the rolling stock used and the harvesting pattern. The transport officers designed locomotive runs and the computer system checked that the set of runs were feasible. It also produced outputs including yard-stock and time-distance charts. CASCHD has now been superseded by the Animated Cane Transport Scheduling System ACTSS, which not only checks the schedule but also produces an animated display.

The first computer program to actually design a set of runs was developed in 1978 by Abel, at James Cook University - ACRSS (Automatic Cane Railway Scheduling System). Abel first proposed that the problem should be decomposed into separate routing and scheduling problems. Sequentially solving these problems produces a trial schedule which can then be refined iteratively.

In 1995, Central Queensland University began work on the production of computer tools to assist traffic officers. The computer program TO Tools has been developed to mirror the operations in most traffic offices. A computer-based spreadsheet replaces the daily ledger with deliveries and collections being shown as spreadsheet entries.

One problem with the packages developed to date is that each program has been developed as a stand alone system. This has resulted in extensive operator training for each tool, with similar data being requested in a different format for each package. (Pinkney and Everitt, 1997)

Cane road transport system

Although a lot of research has been done into monitoring, managing and planning the cane railway transport operation, not the same attention has been given to the road transport system.

The use of the road system offers some advantages in terms of spatial coverage, but the road-based cane transport systems are more complex than those based on rail.

Both capital and operating costs involved with cane road transport are also large. The New South Wales Sugar Milling Cooperative Limited contracts out the cane transport operation to commercial road transport companies. The contract cost is dependent on the number of trucks required. Each truck costs about $250,000 a season to contract and as such there is great financial incentive to minimise the number of trucks in the fleet. (Dines *et al*., 1999)

In order to achieve such an objective one has to

- determine the optimal truck fleet size
- determine the optimal organization of running the haulage system, i.e. especially select the optimal dispatching strategy in order to ensure maximal utilization of the trucks

At the beginning of the harvesting season the mill has to decide upon the number of trucks they will use for transporting the cane from the farms.

About the truck fleet size

The number of trucks, m, in the active fleet results from the inequality relationship between their arrival rate with full bins at the mill and the crushing rate

$$\frac{T_{c,t}}{m} \leq \frac{1}{m} \qquad (1)$$

where $T_{c,t}$ is the average cycle duration of the truck, in hours;
μ is the crushing rate, in bins per hour.

The minimum number of trucks is

$$m^{\min} = \left\lfloor \frac{m}{l} \right\rfloor + 1 \qquad (2)$$

where $\lambda = 1/T_{c,t}$ is the average arrival rate of the trucks at the mill;
$\lfloor X \rfloor$ indicates 'the integer part of X'.

The equality corresponds to the case in which both the arrival and service rate are uniform. This sort of hypothesis has little practical value. The random variation of the arrival and service rate leads to formation of truck queues in the mill yard or idle mill.

Hereafter an analysis of the trucks utilisation (defined as the ratio between the number of trucks in actual operation and their total number) as well as the mill utilization (defined as the actual operation time of the mill) is presented.

The queueing model that best describes this problem is a closed circuit, single server and finite population queueing system. [Figure 1] (Render and Stair, 1982), (Hall, 1991)

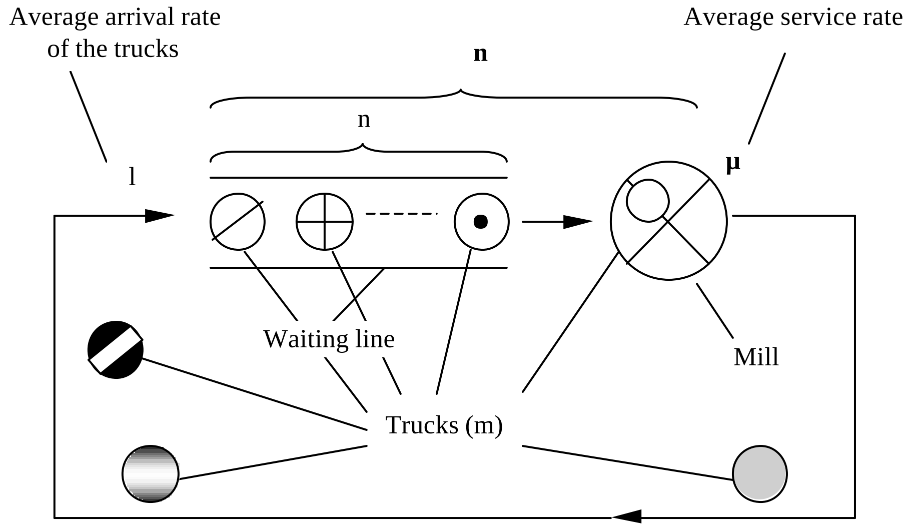
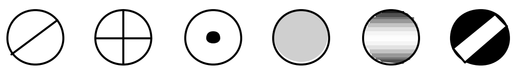


Figure 1 - Single server, finite-population queueing system– closed circuit system

ν – trucks in queue;
n – trucks in queue and service;
n_t = m, total number of trucks;

 - trucks in the system

For the system in Figure 1, if both the arrivals and service rate are exponential (closed circuit system M/M/1) the calculation of the performance parameters is as follows:

The probability of having n trucks in the service system:

$$p_n = \frac{m!}{(m-n)!}\rho^n p_0 \qquad (3)$$

where $\rho = \frac{\lambda}{\mu}$ and

p_0 is the probability of having no trucks in the service system, so the mill is idle:

$$p_0 = \frac{1}{1+\sum_{n=1}^{m}\frac{m!\rho^n}{(m-n)!}} \qquad (4)$$

The average number of trucks in queue:

$$\overline{\nu} = m - \frac{1+\rho}{\rho}(1-\rho_0) \qquad (5)$$

Average number of trucks in the service system (queue and mill):

$$\overline{n} = \overline{\nu} + (1-p_0) \qquad (6)$$

The average time a truck spends in the queue:

$$\bar{t}_q = \frac{\bar{n}}{l\,(m-\bar{n})} = \frac{1}{m}\left(\frac{m}{1-p_0} - \frac{1+r}{r}\right) \qquad (7)$$

The average time a truck spends in the service system (queue and mill):

$$\bar{t}_s = \frac{\bar{n}}{\lambda(m-\bar{n})} = \frac{1}{\mu}\left(\frac{m}{1-p_0} - \frac{1}{\rho}\right) \qquad (8)$$

These calculations are based on an assumed average truck cycle duration of 40 minutes and average crushing rate of 10 bins/h. Summary results are presented in Table 1.

Table 1 - Performance indicators of the system versus number of trucks (m) in the active fleet

m	p_o	$1\text{-}p_0$	$\bar{\nu}$	$\bar{n}$	$\bar{t}_q$	$m-\bar{n}$	α_t
5	0.4045	0.5955	0.4345	1.03	0.073	3.97	0.795
6	0.3101	0.6899	0.711	1.40	0.103	4.6	0.7766
7	0.2280	0.7720	1.081	1.853	0.140	5.15	0.736
8	0.1597	0.8403	1.558	2.40	0.185	5.60	0.70
9	0.1058	0.8942	2.144	3.04	0.24	5.97	0.66
10	0.0659	0.9341	2.84	3.77	0.304	6.23	0.623

$\alpha_t = \frac{m-\bar{n}}{m}$ is the utilization coefficient for the truck (deduct idle time in queue and service)

The m=7 row in Table 1 is highlighted corresponding, as previously explained, to the equality between the arrival and service rates.

Table 1 indicates that the mill utilization, (actual operation time, $1\text{-}p_0$ column) improves as the number of trucks increases, but their respective utilization deteriorates.

Because no cost data (costs associated with idle times of the trucks and mill) were available an optimisation of the number of trucks in the active fleet using the "levels harmonization" technique has been applied. This requires the imposition of a certain minimum level for the mill utilization ($1\text{-}p_0$), and a minimum level for the trucks utilization (α_t). These are marked on Figure 2; the shaded areas (as to the no of trucks) are those which do not ensure the minimum utilization level imposed for the mill, and the trucks. Therefore the acceptable solutions range for the number of trucks is the unshaded area in Figure 2.

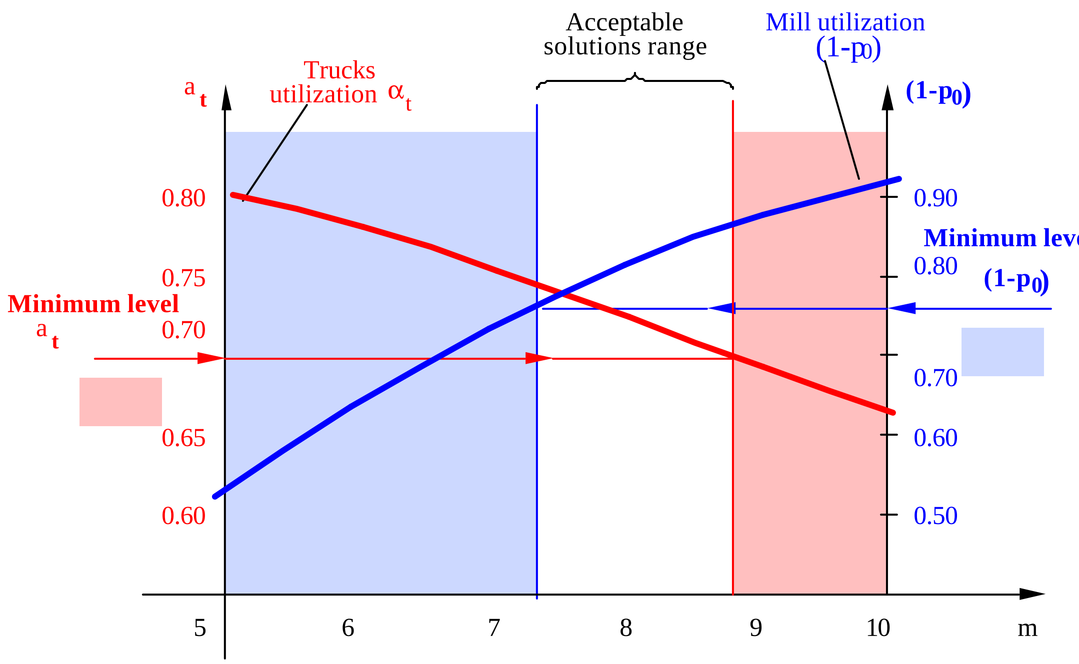


Figure 2 - Levels harmonization for the case study application of the analytical model

The solution obtained using "levels harmonization" has practical value. The minimum levels for α_t and $1-p_0$ can be established from previous experience with the system.

About the dispatching strategy

Optimisation criteria

With the advent of continuous crushing and the accompanying rostered harvesting, the task of managing cane transport operations has become even more complicated. (Pinkney and Camilleri, 1996)

There is a mutually dependent relationship between the growers and millers. Therefore it is essential that the harvesting-transport-crushing system is viewed like an integrated system when addressing any directions.

When considering optimising the operation of this system some specific optimisation criteria need to be established:

A. from the mill's point of view:

- uninterrupted crushing at the forecasted capacity during the whole harvesting season, providing the technical resources are in good working condition;
- limit the effects of accidental stops by modifying the harvesting rate;

- use a minimum number of trucks to haul the full/empty bins;
- use a minimum number of bins.

B. from the farm's point of view:

- assure a harvesting rate according to the resources involved (machines, people);
- avoid the daily significant variations of the resources requirement;
- avoid harvesting interruptions due to the lack of empty bins on the pad;
- minimise cut to crush time (under the critical value)

What is optimum for the mill may not be optimum for the farm, and vice-versa, therefore measures to improve the entire system must be investigated:

C. for the entire process (criteria gathering):

- harvesting-transport-crushing at minimum costs (minimum of resources required) under conditions that maintain the quality of the sugar cane harvested (maintaining the international competitiveness of the Australian sugar industry).

Based on these specifications an interactive simulation model has been developed to facilitate investigations of the optimal use of harvesting, transport and crushing resources.

Case study

The analytical model presented corresponds as mentioned before to exponential arrivals and service rate. Statistical analysis of the data collected from Harwood Mill, NSW showed that such an assumption does not agree with reality: for example in most of the cases truck trip times were described by normal or Erlang distributions, while loading times were best described by uniform distributions. Table 2 indicates some of the observed results for Harwood Mill. (Norusis, 1993)

Table 2 - Harwood Mill data analysis

Pads 6/08/99	Av.trip time	Std.dev.	c.v.	distrib	Av. loading time	Std. dev.	c.v.	distrib
36	26.9	4.9	0.18	normal	43	0	0	uniform
37	25.7	5.9	0.23	normal	75.25	64.5	0.86	negative exp.
52	16.7	6.4	0.38	Erlang(k=7)	47.5	19	0.4	Erlang(k=6)
53	21.7	21.4	0.98	negative exp.	38	6.36	0.17	normal
126	48	4.2	0.09	normal	40	0	0	uniform
147	36.4	7.1	0.19	normal	34	0	0	uniform
148	38.9	3.5	0.09	normal	56.67	39.26	0.69	Erlang(k=2)
176	43.9	7.4	0.17	normal	35	0	0	uniform
200	41.2	3.4	0.08	normal	34	0	0	uniform
222	74.5	6.2	0.08	normal	35	0	0	uniform
223	77.8	14.4	0.19	normal	34	0	0	uniform

Av.mill time	Std.dev.	c.v.	distrib
7.2	3.05	0.42	Erlang (k=6)

In addition the analytical model does not include any representation of the harvesting process, which determines the empty bin dispatching.

Simulation model

Simulation studies can contribute a lot towards solving the problems associated with the operation of a complex system, such as the cane harvesting-transport-crushing system. In order to obtain reliable and meaningful results from simulation studies, under these circumstances, one has to take into account the conditions, restrictions and requirements of the real operation in its very complexity and details:

- the mathematical model does not describe reality well
- arrivals and service rate are not always exponentially distributed (tedious computations otherwise)
- harvesting system is not explicitly presented
- empty bin trucks dispatching is not random
- avoid lack of empty bins at the farms
- conform to the critical cut to crush time
- harvesting is a stochastic process
- harvesting and transport daily duration are different

Another characteristic of the problem is that mills control the harvesting process by controlling the supply of empty bins to the farms.

The main characteristics of the system that set this simulation model apart from other similar problems can be summarized as follows:

- two commodities
- perishable product
- demand pattern is a decision variable
- most of the elements are stochastic

Computer simulation of the system operation under given technological conditions seems to be the most appropriate alternative in order to ensure the correlation between the number of available bins and the size of the active truck fleet.

The case of constant harvesting and arrival rates of the trucks with empty bins represents an ideal situation for the operation of the system, and is hard to believe it can be achieved even with a sound operative management system in place. That is the reason why for the actual values of l_e (average arrival rate of the trucks with empty bins) and m(average bin loading rate), the Dn'_e value of the empty bins stock has to be checked, in order to avoid the stockout, with consequences for the harvesting flow during $W_{h/day}$ (daily harvesting period). Computer simulation, treating l_e and m as discrete random variables can be the most convenient way to check on and eliminate the stockout, for a certain initial stock value. The operations management system has to attempt avoiding the harvesting interruptions due to the temporary lack of empty bins on the pad.

Model implementation required the choice of a suitable computer programming language. Two broad choices were possible: (1) the use of special purpose simulation languages, or (2) the use of a general programming language.
All of the standard simulation software considered, including those specialised in transport and transfer of flows, were not completely suitable for the problem. (Imagine That, Inc.), (InterDynamics Pty Ltd.), (Banks and Carson, 1984). They all contain predefined functions that cannot deal with the dispatching of the trucks after unloading according to the dynamic evolution of the situation at the farms. The dispatching rule needs to be defined by the analyst and consists of the priority given to the avoidance of empty bins stockout at the farms with consequences for the harvesting process, and to the bins older than the critical cut to crush time.

Thus special-purpose simulation languages are not flexible and versatile enough for the problem, and programming languages for discrete-event systems simulation do not have the facilities in order to decide the destination of the trucks after unloading.

On the other hand general programming languages are flexible, allow data base management (empty and full bins inventory), and outputs are non-standard.

Given that the model required some customised features to fit the actual system operations, a general programming language was therefore the most suitable choice. Thus the interactive simulation model was built using the programming capabilities of Microsoft Visual FoxPro software for Windows, which is an object-oriented environment for database construction and application development. (Raicu and Taylor, 2000a)

The simulation model developed has the following properties:

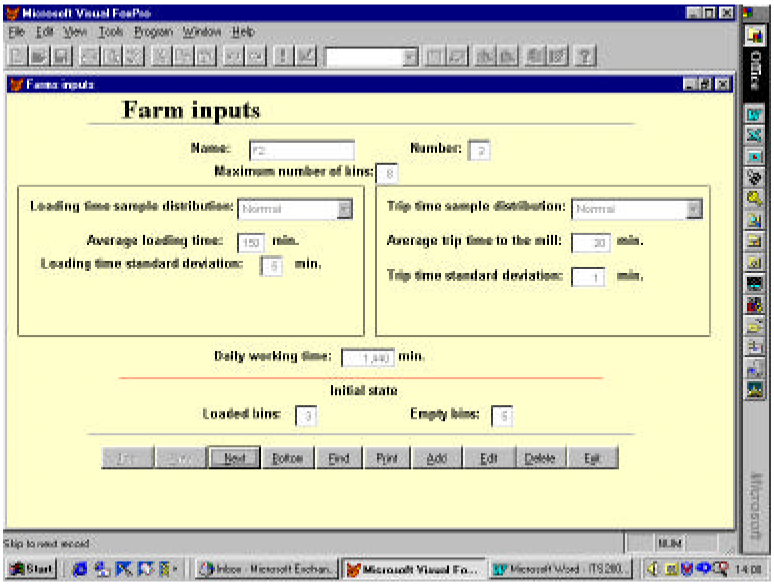
- describes the system well at an appropriate level of detail
- utilises the available data from the harvesting-transport-crushing system
- deals with random events - exponential, Erlang, normal or uniform distributions
- uses a database for empty and full bins at each farm
- allows resource changes (no farms, no trucks)
- simulation time is 30 days in order to diminish the effects of the initial state of the system
- allows changes of harvesting and transport operation time
- outputs represent significant performance indicators for farms and mill

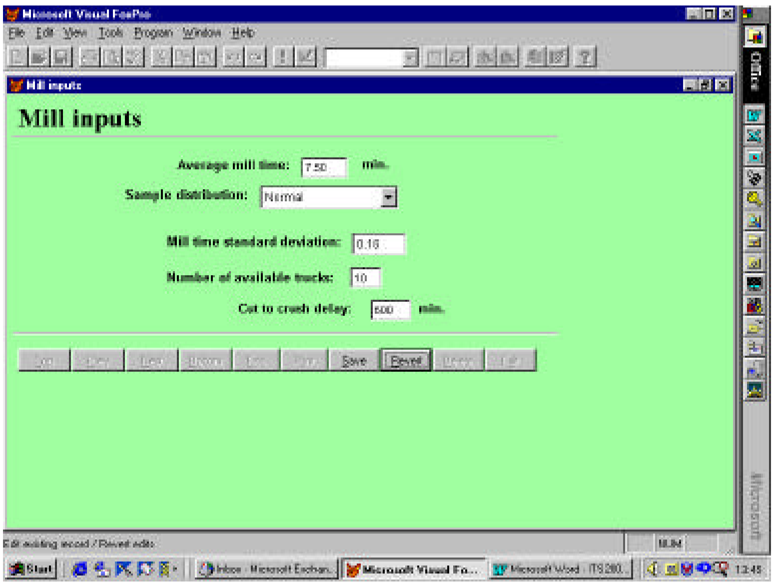
The most common and economic operational cycle - the truck brings an empty bin to the pad, loads a full bin off the same pad, and hauls it to the mill - is used to simulate the process. The trucks operate continuously for 24 hours/day, while the harvesting is completed during the daylight time (say 14 hours/day).

Basic input variables

The basic input variables of the system:

- farm inputs: number of pads, maximum number of bins that can be stocked on each pad, loading time of a bin (harvesting rate), round trip time (truck cycle duration)- collected using Global Positioning System (GPS) receivers in each truck and from daily working hours;
- mill inputs: number of available trucks, service time (crushing rate), critical cut to crush time. Figure 3 shows examples.





GPS allows the capture of positional and time data for each truck within the fleet which can then be GIS integrated using a typical multilayer GIS software such as Mapinfo - see Figure 4 for an example GIS plot of vehicle locations.

Due to the continuous tracking by GPS any deviation from the correct route can be acknowledged and the appropriate message sent to the operator to change course. This facility can also be used as a part of an incident detection system. Events frequently occur that disrupt the planned schedule. Examples are cuts to the mill's cane requirements and the resulting changes to the harvesters' allotments, or the inability of a harvester to supply the required amount of cane. Providing the traffic officers with this real time information enables them to more effectively reschedule the operation. (Raicu and Taylor, 2000b)

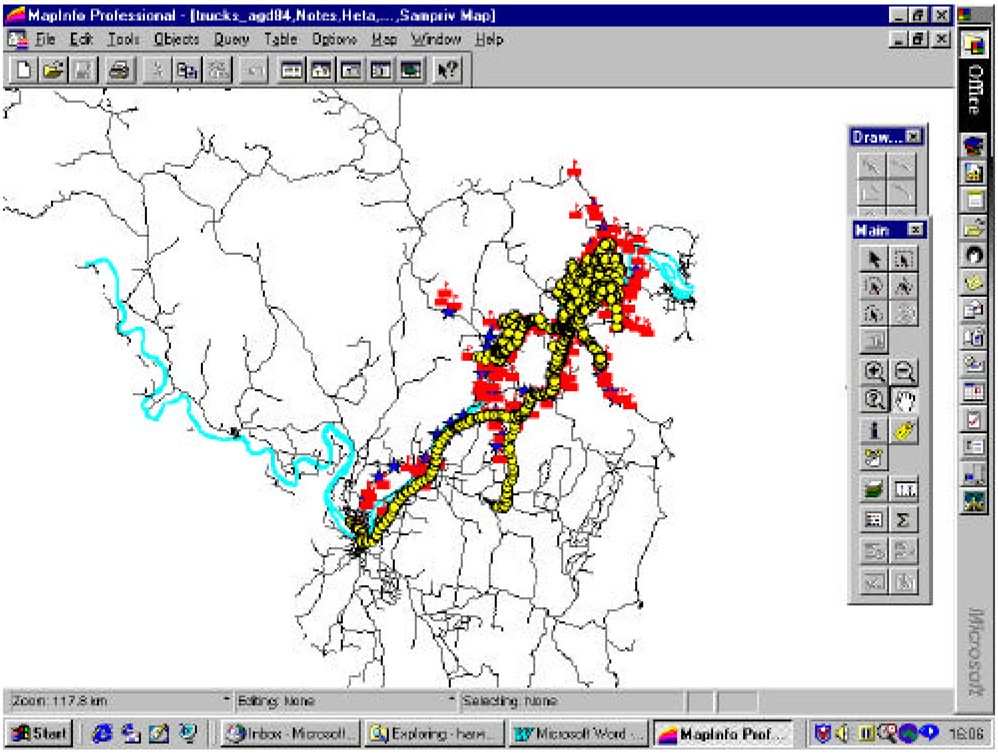
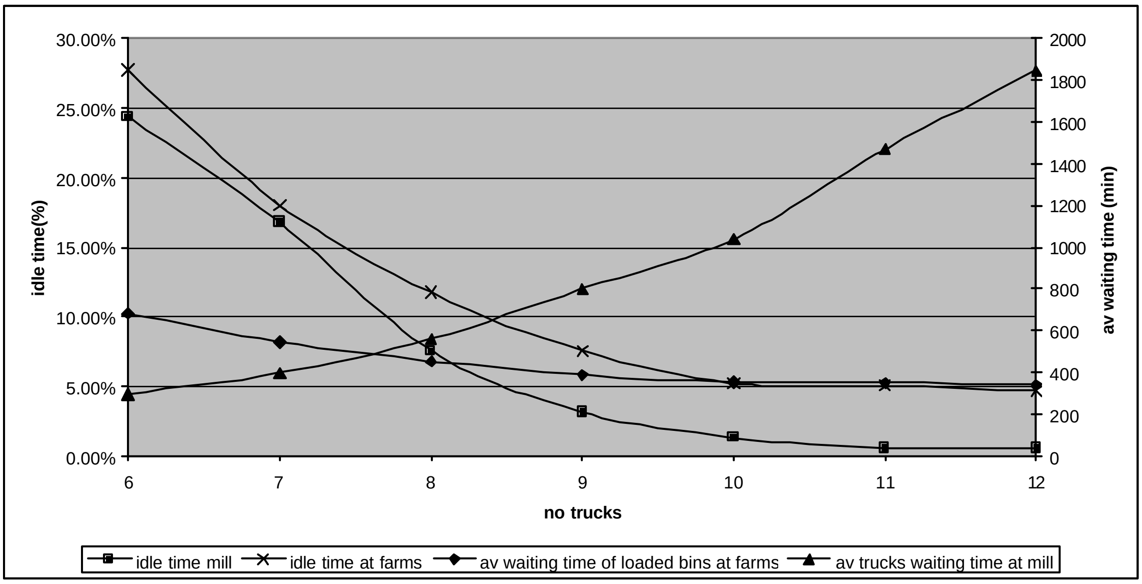


Figure 4 - Local road network and vehicle locations, Harwood Mill, NSW

Main output variables

- ➢ average trucks waiting time at the mill;
- ➢ average trucks queue length;
- ➢ total idle time of the mill;
- ➢ average waiting time of the loaded bins on the pads;
- ➢ number of bins that waited more than the cut to crush critical time after loading;
- ➢ idle times at farms due to lack of empty bins. [Figure 5]

The results presented in Figure 5 were obtained after a series of simulations using 1999 season data from Harwood Mill, NSW.



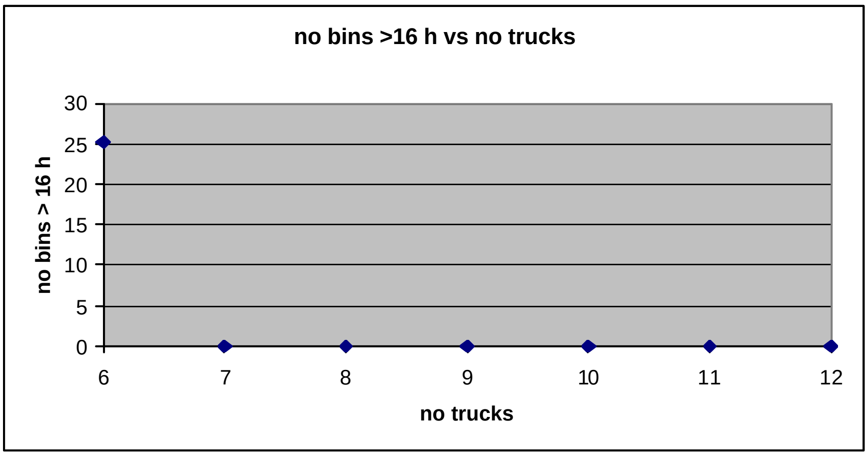


Figure 5 - Results of simulation

The examination of these results leads to some interesting findings:

- performance indicators as the average idle time at farms due to lack of empty bins, the average waiting time of the loaded bins at the farms, the total idle time of the mill, the number of bins hauled to the mill, and the number of bins older than the critical cut to crush time improve as the number of trucks increases;
- performance indicators as the average trucks queue length (or the average trucks waiting time at the mill) deteriorates as the number of trucks increases.

Thus, for a fleet of 10÷12 trucks all the performance indicators are very well behaved except for the average trucks queue length in the mill yard that reaches maximum values; for a fleet of 7 trucks, the queue length in the mill yard drops to a minimum, and there are no bins older than the critical cut to crush time in the system, but all the other performance indicators deteriorate. Therefore when looking for an optimum in terms of fleet size the two contrary effects have to be balanced.

The simulation model determines the number of trucks required in order to ensure uninterrupted crushing at the mill, uninterrupted harvesting (avoiding a lack of empty bins on the pad) and comply with the cut to crush critical time interval.

Designed as an interactive model, the simulation allows changes of the transport, harvesting and crushing resources characteristics.

The simulation model can establish the dependency between the number of trucks in the active fleet and mill's performing parameters, and harvesting parameters at each farm.

Observations

Simulation takes into account as mentioned before the most frequent scenario, namely the usage cycle for the truck which appears to be the most rational for the steady operation state of the system, but this is not the only one found in actual operation. Even if the other operational cycles do not occur as frequent they cannot be omitted from the preoccupations of optimisation of the system.

A similar approach can be applied to solve other important transport problems. The road transport of containers between the terminals of different transport modes (rail, port) and the beneficiaries that can be served only by road is a similar problem. A solution as the one presented above would optimise the use of resources (vehicles, fuel, people, containers) and diminish pollution and congestion on the main urban road arteries (mainly by eliminating the dead-runs).

Conclusions

The simulation model developed is not Harwood Mill specific; it can be used for planning purposes at any of the sugar cane mills using road transport system exclusively. Being designed as an interactive model it allows changes of the resources characteristics.

Simulation proves to be a useful tool for predicting the performance of the transport cane delivery system in various scenarios. It is relatively easy to also identify areas where optimisation is needed such as the number of trucks in the active fleet as a function of the operation and slack costs related to transport, harvesting and crushing. The difficulties of combining the optimisation criteria can be eased by adopting some harmonization levels for the use of transport, harvesting and crushing resources as demonstrated before.

Continuous vehicle tracking (GPS) delivers more accurate simulation models due to accurate and effective collection of a great volume of operational data, while at the same time enables traffic officers to more effectively schedule (reschedule) the operation in real time. Safety is an important feature of the system, too.

The simulation model will provide the cane traffic inspectors with a method for optimising the resources of the harvesting-transport-processing system over large horizons (entire harvesting season) while at the same time planning the day to day operation. This will lead to productivity gains in the mill cane supply operations by minimising operating expenses and the maximum utilization of capital.

References

Banks, J and Carson, JS (1984) Discrete-event system simulation, Prentice-Hall, Inc., New Jersey.

Dines, G Petersen, GJ and Worth, RT (1999) Productivity Advances in a Road Transport Cane Delivery System, in Proceedings of the Australian Society of Sugar Cane Technologists, Townsville, 468-473.

Hall, RW (1991) Queueing methods for services and manufacturing, Prentice-Hall, Inc.

Imagine That, Inc., Extend- simulation software for the next millenium, http://www.imaginethatinc.com/extend_details.html.

InterDynamics Pty Ltd., Planimate-Animated Planning Platforms, http://www.interdyne.com.au.

Keating, B and Wilson, J (1997) CAB International, Intensive Sugarcane Production:Meeting the Challenge Beyond 2000, in Proceedings of the Sugar 2000 Symposium, Brisbane.

Norusis, MJ (1993) SPSS for Windows Base System User's Guide Release 6.0, SPSS Inc.

Pinkney, AJ and Camilleri, C (1996) Computer based traffic officer tools, in Proceedings of Australian Society of Sugar Cane Technologists, Mackay, 303-309.

Pinkney, AJ and Everitt, PG (1997) Towards an Integrated Cane Transport Scheduling System, in Proceedings of Australian Society of Sugar Cane Technologists, 420-425.

Raicu, R and Taylor, MAP (2000a) Development of a model for sugar cane road transport, in Proceedings of Australian Society of Sugar Cane Technologists, Bundaberg, 525.

Raicu, R and Taylor, MAP (2000b) Integrated GPS/GIS for use in monitoring, modelling and managing cane harvest transport systems, in Proceedings of 7th World Congress on Intelligent Transport Systems, Turin.

Render, B and Stair, MRJr. (1982) Quantitative Analysis for Management, Allyn and Bacon, Inc.

Sugar Research and Development Corporation (1999) Research and Development Plan 1999-2004.