Australian Sugar Mills Optimize Harvester Rosters to Improve Production

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Increasing cost/price ratios in sugarcane production and the pressure to remain internationally competitive have forced Australian sugar mills to try to use their infrastructure more efficiently. Generating rosters for sugarcane harvesters manually is difficult because the mills have a large number of harvesters and tight capacities in the transportation facilities. The Cooperative Research Centre for Sustainable Sugar Production conducted a participatory research process with five mills in the Australian sugar industry to develop models to optimize harvester rosters. Embedded in the research process and underpinned by action learning was the development of a novel integer-programming model, its validation, and its implementation. The participatory research overcame barriers to implementation of the rosters produced by the model and allowed the five participating mills to realize benefits in terms of more efficient transport operations.
(*Industries: agriculture, machinery. Programming: integer, algorithms, heuristic.*)

In most countries that grow sugarcane, a sugar mill crushes about 1.5 million tons of cane annually, given a harvest season of between 20 and 40 weeks during which the mill operates continuously. To supply the mill with this much cane, approximately 80 mechanical cane harvesters must be operated each day throughout the region containing the farms that supply the mill. This is a typical scenario in many advanced sugar-producing countries, such as Brazil, Australia, the United States, and South Africa. In some countries, including Australia, the mechanical harvesters are privately owned and each owner-operator has contracts for between one and 20 farms. During the harvest season, the harvester operator removes all of the cane from its contracted farms. As the harvester cuts cane, it fills a bin on wheels hauled by a tractor next to it. When the bin is full, the tractor transports it to a nearby railway siding (in the case of rail transport). The cane is then poured from the tractor-hauled bin into the rail-wagon bin. When enough full rail-wagon bins have accumulated, a locomotive hauls them to the mill. Australia has 30 mills, mainly located on the tropical north-east coast and serving a total area of 400,000 hectares (about 15,000 hectares per mill). Twenty six of these mills own the narrow-gauge rail network over which the trains operate. Newer farms that are some distance from the rail network rely on road transport. From six to 16 hours elapse between when the harvester cuts the cane and when the mill starts processing the cane to produce raw sugar, depending upon the transport schedule and how long it takes to transport the cane to the mill. The costs of harvesting and transport in Australia are approximately 25 percent of the total cost of sugar production (Grimley and Horton 1997), which is about A$20 million per year per mill.

For nearly all mills in Australia, harvester operators work 12-hour daytime shifts and work fewer than seven days per week. Most harvester operators specify the number of days per week they work and the mill constructs a roster to schedule them. Other harvester operators specify which days they will work, such as Monday to Thursday. How many days they work are

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dictated by socioeconomic issues as well as by the amount of cane to be harvested. In setting the roster (scheduling harvesters for days of the week), the mill considers several factors, including the capacities and schedule reliability of the road and rail transport facilities for transporting cane and its ability to ensure an uninterrupted supply of cane to the mill. A poor roster can mean days when too few harvesters cut cane to keep the mill operating continuously.

Because of increasing cost/price pressures in the Australian sugar industry, mills sought more efficient and cost-effective use of infrastructure. They were finding it too difficult and expensive to generate rosters that would keep the mills operating continuously and prevent increases in harvesting, transportation, and milling costs. Scheduling harvesters had become difficult because the land under cane had increased, causing greater pressure on the existing infrastructure. Also, industry deregulation allows harvester operators to work across multiple mill regions. The Australian sugar industry wanted to accomplish the following:

(1) To provide more reliable transportation of cane for harvesters to reduce harvesting costs;

(2) To ensure a more constant daily supply of cane to the mills to reduce the number of expensive mill stoppages;

(3) To better utilize infrastructure, including bin fleets, and rail and road transportation facilities;

(4) To decrease capital expenditure by improving utilization of existing facilities; and

(5) To reduce the costs of developing rosters (it currently takes about 15 man-days to produce a harvester roster).

Realizing these goals was difficult because

- Mill planning staff had built up expertise and had reservations about accepting new technology because of all of the reasons it could not work;
- Physical and socioeconomic constraints on the system were difficult to quantify; and
- The Australian sugar industry consists of a regulated group of privately owned farms and harvesters and a separately owned mill, none of which should suffer detrimental effects.

To realize these goals, about 15 planners and managers from five mills within the Australian sugar industry located in the Mackay region, Queensland (Mackay Sugar Co-operative owned the Farleigh, Marian, Pleystowe, and Racecourse mills, while CSR Ltd owned the Plane Creek mill) and two researchers (including myself) from the federal-government-funded Co-operative Research Centre for Sustainable Sugar Production and Commonwealth Scientific and Industrial Research Organisation (CSIRO) engaged in

> The greatest improvements came from reducing variability in daily bin supply to the mill.

participatory research (Martin and Sherington 1997). The research, which the managers and planners from the mills initiated, was linked to participatory implementation of changed practices. The participants used an action learning approach, described by McGill and Beaty (1995), as a forum for collective self-reflective inquiry that they undertook in social situations to improve practices or to address shared concerns or opportunities. The participatory research overcomes the mismatch of researchers' and end-users' knowledge systems, overcomes barriers to implementation, and ensures that the industry client owns the project. This ownership was critical because businesses in the Australian sugar industry are conservative and are understandably skeptical about research outputs, particularly when implementation difficulties arise. Under participatory research, the team of mill planning-staff members and researchers developed and validated the model and implemented it. The workshops gave participants a way to learn from their own experience, to take action, and to make their experience available to others in the partnership, which was critical for successful implementation. Participatory research has been used to address other issues and has added value, for example in assessing alternative grain-cropping-system practices (Robertson et al. 2000), for planning improved sanitation services in Alaska (Berardi and Donnelly 1999), and for implementing alternative arrangements for supplying sugarcane (Muchow et al. 2000).

We developed and solved a constrained nonlinear integer programming model to optimize harvester rosters. The result is an original operations research application and a robust model that is easily adapted to sugar mills with different harvesting and transport systems. For five large Australian sugar mill regions that participated in the research, we implemented the model during the 2000 harvest season.

Participatory Research Process

The industry initiated the research, specifying the key issue to be addressed and forming a partnership with the researchers. The researchers began developing a model and validating it in mid-1999 based on that year's manually generated harvester rosters. The project relied on participatory research linked with action learning, with the following key elements:

- The research focused on outputs and outcomes that would benefit industry. Implementation was built in over the life of the project. Without participatory research, the focus might have been academic science.
- The measure of success was return on the investment in research.
- Industry participants and researchers were equal partners in the research process: The industry members of the team included mill managers, transport officers, and field staff who interact with the harvester operators and growers. The interaction between researchers and industry workers was at the same level as that between researchers and their colleagues. This interaction produced better and faster learning by all participants and increased the researchers' ability to add value to industry operations.
- The research consisted of a series of cycles (plan, action, reflect, revised plan), which underpinned the action-learning cycle, enabling participants to learn through the model development, validation, and implementation so as to direct these processes towards delivering maximum benefits.

The model development and validation phases were effective because the industry partners understood the model. The first pass of model development and validation, which started mid-1999, took two months. The team made about six revisions per mill during the "reflective phases" of the action-learning process. These revisions took eight months until mid-2000 when the mills implemented the rosters. The team has continued to make further revisions since then to improve implementation and achieve greater benefits.

Model Development

First, I will describe sugarcane harvesting and transport. From the season start to finish, the mill and its transport system operate continuously, unless there are breakdowns. In rail transport, rail-wagon bins, carrying sugarcane, are hauled by locomotives along the

For 2001, representatives from the mills estimate that the industry can save A$260,000.

narrow gauge railway to mills, with 25km being an average distance of haulage. Different bin types have different capacities, such as four tons and six tons. Most harvester operators work from 6:00 am to 6:00 pm, creating a risk of a shortage of cane to the mill from about 6:00 am to 8:00 am, since the earliest the cane can arrive at the mill when harvesters start at 6:00 am is 8:00 am. About 20 percent of the harvesters start at about 3:00 am to overcome this problem, allowing delivery of early bins to the mill prior to 8:00 am. The number of early bins should remain fairly constant from day to day to ensure that the mill does not have a shortage of cane.

A mill's rail network contains about 150km of track with up to 10 major branches and up to 200 sidings. These sidings are short sections of rail track that run parallel to the main line, which are used for storing full (wagon) bins and for storing empty bins waiting to be filled. A siding's capacity is defined by the number of bins it can hold and by the number of harvesters that can use the siding in any one day. Potential clashes between harvester operators wanting to use a siding at the same time can be reduced by adding sidings to the rail network, but doing so increases transport capital costs. The cane train visits a list of sidings to pick up full bins or deliver empties in a loco run, which is usually confined to an individual rail branch line. Cane is also delivered to the mills by trucks, which transport wagon bins to the mill. In modeling the process, we treated loading points the same way we treated rail sidings, and we treated a group of loading points (a road-transport area) in a similar way to a loco run.

From the start, the industry participants emphasised what decision results they needed. They needed a roster pattern for each harvester that covered a set of days to cut cane. The roster covers 49 days after which it repeats (Table 1). Unless a harvester operator asks for a fixed roster pattern (for example, Tuesday through Friday), it is assigned to one of seven permissible patterns, determined by whether the harvester operator works six out of seven days, five out of seven days, and so on.

An industry priority was setting the right objective function, so that a roster produced by the model would produce the desired outcomes when implemented. The industry partners saw a weighted multiobjective function as essential because mill regions differed in their priorities and mill planning staff wanted to analyze various options. Through trial and error in collaboration with each of the mills to determine the appropriate weighting, we were able to produce a near-optimal roster for each mill. The objective was to minimize a weighted combination of the following components:

(1) Variability of daily bin or cane supply to the mill for each bin type;

(2) Variability of daily early bin supply to the mill;

(3) Variability of daily siding usage to minimize the risk of clashes among harvesters; and

(4) Variability of daily locomotive runs or road transport area usage to maximize transport utilization.

The first two components ensure that the mill has a smooth and uninterrupted supply of cane to crush

Pattern	Day													
j	1	2	3	4	5	6	7	8	9	10	11	12	—	49	
1	0	1	1	1	1	1	1	1	0	1	1	1	—	0	
2	1	0	1	1	1	1	1	1	1	0	1	1	—	1	
3	1	1	0	1	1	1	1	1	1	1	0	1	—	1	6 days out of 7
4	1	1	1	0	1	1	1	1	1	1	1	0	—	1	
5	1	1	1	1	0	1	1	1	1	1	1	1	—	1	
6	1	1	1	1	1	0	1	1	1	1	1	1	—	1	
7	1	1	1	1	1	1	0	0	1	1	1	1	—	1	
8	0	0	1	1	1	1	1	1	0	0	1	1	—	0	
9	1	0	0	1	1	1	1	1	1	0	0	1	—	1	
10	1	1	0	0	1	1	1	1	1	1	0	0	—	1	
11	1	1	1	0	0	1	1	1	1	1	1	0	—	1	5 days out of 7
12	1	1	1	1	0	0	1	1	1	1	1	1	—	1	
13	1	1	1	1	1	0	0	0	1	1	1	1	—	1	
14	0	1	1	1	1	1	0	0	0	1	1	1	—	0	
						↓					↓				
41	0	0	0	0	1	0	0	0	0	0	0	0	—	0	1 day out of 7
42	0	0	0	0	0	1	0	0	0	0	0	0	—	0	

Table 1: The above is a sample of the roster pattern combinations with a "1" representing a day when the harvester operator works, and "0" a day when the harvester operator does not work. No matter how many days out of seven the harvester operator works, there are seven permissible patterns, unless the harvester operator is on fixed days.

each day. The amount of cane actually crushed by the mill is not identical to the amount rostered because of variability in weather and in the quality of cane, and milling problems. A roster with low variability in day-to-day supply of cane reduces the risk of mill stoppages caused by too few harvesters rostered on some days. Minimizing the first two components also allows the best utilization of the bin fleet. Great variability in bin supply to the mill from day-to-day means great variability in the number of bins the harvesters require. The bins cost about A$5,000 each, and an average mill uses about 2,500 of them. Minimizing the third component minimizes the risk of two or more harvester operators wanting to use the same siding on the same day. The mill planners are unlikely to implement a roster that risks clashes between harvesters. Better utilization of sidings also means fewer delays for harvesters and less pressure on the mill to increase the number of sidings. Minimizing the fourth component reduces capital costs because the existing infrastructure is better used and reduces harvesters' idle time because empty bins reach harvesters more reliably.

The best weighting of the four components varied by mill region because of differences in infrastructure and operations. We set the weights of the components through an action-learning cycle in collaboration with planners from each mill region. We tried different weights and validated the resulting rosters. Trying different weights showed how sensitive the roster was to different weighting values. It was difficult to arrive at an ideal roster for all four components. Industry involvement was critical in sorting out priorities. Through this action-learning process, we achieved weights that produced rosters that industry members were confident would best deliver desired outcomes.

The model formulation we developed is unique in the literature (Appendix), but the decision variable and the permissible patterns are similar to those in a nurse-scheduling problem described by Dowsland (1998). Researchers have found near-optimal solutions to rostering problems using exact (Caprara et al. 1998) and heuristic techniques, including simulated annealing (Brusco and Jacobs 1993), and tabu search (Dowsland 1998). We used a slight extension to the general tabu search technique (Glover 1993) to solve the harvester rostering problem for the following reasons:

- We needed a robust solution technique to conduct options analyses that required changes to the objective function.
- We wanted to avoid having to fine-tune the solution-technique parameters to achieve desirable rosters for different mills or options analyses, largely to make the model easy for mill planners to use.
- We did not require a short CPU time because the existing manual methods took several man-days.

The tabu search (Appendix) required an initial roster. We used two methods for producing an initial roster:

- When the mill planning staff had made a quick attempt at constructing a roster manually using past experience, the resulting rosters provided an excellent starting point for the tabu search.
- Random allocation of a permissible roster pattern to each harvester provided a usable starting point for tabu search. We used this method from 2000 on because mill planners no longer construct rosters manually.

For the mill regions in which the mills implemented the rosters, the tabu search converged to the best roster found within two hours on a Pentium III 550.

Validation and Implementation

Through participatory research, we conducted a series of validations primarily using the 1999 harvest season for pilot rosters. This season was fresh in everyone's mind since we carried out the validation process while the mill was using those rosters. The mill planners from the five mills validated the near-optimal rosters (produced by the model) using expert knowledge provided by the traffic officers, a rail-transport simulation model within the mill, and local information about each harvester and its operator. They also checked harvester-to-farm logistics, such as the ability to physically move mechanical harvesters from farm to farm according to the roster. While the planners had agreed upon the model constraints, and the rosters met these constraints, in the validation they tried to cover all unquantified constraints that could make it impossible to implement the roster produced by the model. Many of these unquantified constraints could not be known before the planners saw the rosters. It was impractical to include these constraints in the model because most were difficult to quantify or had an impact on the roster only under special circumstances. The validation did highlight cases in which the rosters were impractical. We overcame these barriers to implementation, which mainly concerned rail transport and harvester operator socioeconomic issues, by amending the roster pattern for some harvesters. After at least one more validation process, the team members agreed that no further barriers to implementation existed if the five mills were to use the rosters produced by the model for 1999. We agreed to develop and implement model rosters for the 2000 harvest season, since the 1999 rosters that had been manually developed were already fixed and could not be changed.

Roster validation included assessing the advantages of model-generated rosters over those developed by the mill staff (Table 2). The greatest improvements came from reducing variability in daily bin supply to the mill (across the 49 days in the roster cycle), with up to a 94 percent reduction. The slightest improvements came from reducing the risk of siding clashes (that is, reducing variability in daily siding usage). When planning a roster manually, the mill planners first make sure that the potential for siding clashes among harvesters needing to use the same siding on the same day is minimal. This task is not difficult when one is considering each siding individually, because more than five harvesters rarely use the same siding. However, while mill planners easily avoid siding clashes, it is difficult for them to address this problem, loco run usage, road transport, and daily bin supply simultaneously. This is where the model produced significant improvements (Table 3 and Figure 1).

For the 2000 harvest season, we had less than five weeks between obtaining the input data for the model (information on harvesters availability) and the due date for the final rosters. Industry participation to validate the rosters produced by the model was critical because planners for two of the mills were producing these rosters manually because they doubted that the model's rosters would be implementable. Largely because the harvester operators made last-minute changes, we had to revise the draft rosters. Three of the five mills implemented the rosters produced by the model after they were validated. Because of planners' reservations and time limitations, the Farleigh and Marian mills amended the roster patterns for some harvesters. They had reservations about the model's rosters mainly because they looked different from those they constructed themselves. Major changes in the roster left radical changes in the road transport schedules, which also caused anxiety. Despite the Farleigh and Marian mills amending the roster patterns for some harvesters in 2000, the planners from all five mills agreed that the rosters produced by the model were far superior to those they could create manually. The 2000 model rosters that the Racecourse and Pleystowe mills implemented were similar in their variability in daily bin and siding usage to the 1999 model rosters that we had compared to the rosters actually used in 1999 (Table 2, Figure 1).

Outcomes for Industry and Avenues for Further Value-Adding

After the 2000 harvest season, we held a workshop with the planners from the five mills to assess the benefits from the first year of implementation. Although we

Mill	Variability of Daily Bin Supply to Mill	Variability of Daily Bin Supply (early)	Daily Loco Run Variability	Daily Siding Usage Variability
Farleigh	92	N/A	84	15
Pleystowe	93	66	96	9
Marian	83	64	74	35
Racecourse	86	62	84	22
Plane Creek	94	93	65	54

Table 2: Improvements (%) in model roster versus mill roster for the 1999 harvest season. For the comparison, we used model rosters after validation and the mill-generated rosters as those applied in 1999. An N/A means it is not applicable to that mill.

Harvester	Roster	Harvest Day 1	2	3	4	5	· ·	49
1	5	14	14	14	14	0	· ·	14
2	4	30	30	30	0	0	· ·	30
3	4	33	33	33	0	0	· ·	33
4	7	0	0	0	0	97	· ·	0
:	:	:	:	:	:	:	· ·	:
93	2	71	0	71	71	71	· ·	71
94	7	0	65	65	65	65	· ·	0
Total bins		2,275	2,313	2,296	2,284	2,265	· ·	2,242

Harvester	Roster	Harvest Day 1	2	3	4	5	· ·	49
1	6	14	14	14	14	14	· ·	0
2	1	0	0	30	30	30	· ·	30
3	1	0	0	33	33	33	· ·	33
4	4	0	97	97	0	0	· ·	0
:	:	:	:	:	:	:	· ·	:
93	6	71	71	71	71	71	· ·	71
94	7	0	65	65	65	65	· ·	0
Total bins		2,320	2,302	2,140	2,221	2,543	· ·	2,276

Table 3: In the roster developed by the optimization model (top) and the roster developed by mill planning staff (bottom), a "0" ton entry is a roster day off. In the roster column, a "1" means the first roster day off is on day one, and likewise with a roster value of 2, and so on. The "Total bins" row represents the total bin supply to the mill at each day for all 94 harvesters (the first four and last two are shown). Even with six out of the 49 days shown in the cycle, the "Total bins" is clearly less variable for the model-generated roster as the difference between the minimum and maximum total bins is less than one-third of that with the mill-generated roster. This is further evident in Figure 1 for Pleystowe mill, which shows the total daily bins across the 49 days in the roster cycle for the mill and model rosters.

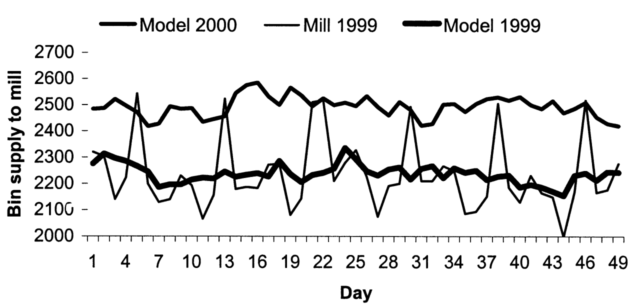

Figure 1: In this comparison of the daily bin supply to Pleystowe mill for the rosters produced by the model for 1999 and 2000 and the roster produced by mill planners in 1999, it is clear that the variability of the rosters produced by the model is far less than that for rosters produced by the mill planners.

could not quantify dollar gains, the representatives from the mills confirmed benefits over previous years: (1) delivery of empty bins to harvesters had been more reliable; (2) utilization of the different bin types had improved; and (3) the use of existing transport infrastructure had been more reliable. The mills' personnel were satisfied with the value added by the rosters produced by the model for the 2000 harvest season, and they asked for the development of an end-user version of the model. For 2001, representatives from the mills estimate that the industry can save A$260,000 per year for the five mills by more completely implementing the model rosters (without mill planners needing to amend rosters) and by capitalizing on the efficiency gains demonstrated in 2000. The mills agreed that the validation process in 2000 could be scaled back significantly for 2001 and beyond, thus reducing the time needed to produce a roster by the 15 man-days it took for manual methods. Because we demonstrated the value of optimizing harvester rosters, nearly half the remaining sugar mills in Australia have sought involvement in the research process.

The industry is now pushing to optimize harvester rosters, siding rosters, and cane-transport schedules in an integrated manner. We are carrying out this research as part of our ongoing work, anticipating that we will further reduce capital expenditure for transport and further improve operations. Like many primary industries, the Australian sugar industry is traditionally seen as a series of independent components: farming, harvesting, transport to the mill, milling the sugar, marketing, and shipping. Research has focused mainly on the individual components, but the industry increasingly wishes to be addressed as a set of integrated components. Research addressing the individual components is less and less able to add value, and researchers need to conduct systems research to enhance the Australian sugar industry's international competitiveness. The industry needs to integrate optimization of all components, including transport (Abel et al. 1981) and cane supply (Higgins 1999), and economic, forecasting, and resource management. Grimley and Horton (1997) estimated the potential long-term cost saving to the industry as A$2.80 per ton of cane per year.

Conclusions

We showed that participatory research between industry and scientific researchers was effective in implementing harvester rosters produced by an optimization model. Through this process, we overcame barriers to implementation, such as socioeconomic constraints and reservations towards new technology, which the standard scientific research and development paradigm would not have achieved. However, participatory research linked with action learning is expensive and time consuming compared to the standard research paradigm and requires scientific researchers to be committed to working with industry over the long term to ensure an eventual successful implementation. The planners from the five mills that implemented agreed there were significant benefits in 2000, but in light of this success, they have also agreed that there are many ways to further refine and advance the work (for example, integrating with rostering of siding usage and scheduling of transport), which were not planned at the start of the research process.

Appendix

The Harvester Rostering Model

The index sets and parameters used to describe the harvester rostering problem are as follows:

I = the set of harvesters that cut cane within the mill region.

K = the set of harvest days in the roster. The harvest roster repeats every seven weeks. Therefore $K = \{1, \ldots, 49\}$.

J = the set of roster patterns, where each pattern contains the days harvesting and days off for each of the 49 days.

R = the loco runs (or branch lines) within the mill's rail-transport network.

S = the set of sidings or road-transport loading points in the mill region.

T = the set of possible bin types.

$$a_{jk} = \begin{cases} 1 & \text{if pattern } j \in J \text{ has harvesting} \\ & \text{on day } k \in K, \\ 0 & \text{otherwise.} \end{cases}$$

Table 1 contains an illustration of a_{jk}.

b_{it} = bins per day of bin type $t \in T$ for harvester $i \in I$.

$b_i = \sum_{t \in T} b_{it}$, the total daily bins for harvester $i \in I$.

e_i = early bins per day for harvester $i \in I$.

$$f_{ij} = \begin{cases} 1 & \text{if harvester } i \in I \text{ is permitted} \\ & \text{on pattern } j \in J, \\ 0 & \text{otherwise.} \end{cases}$$

p_{ir} = proportion of time harvester $i \in I$ supplies cane to a siding on loco run $r \in R$.

q_{is} = proportion of time harvester $i \in I$ supplies cane to siding $s \in S$.

The above proportions are determined using the preseason forecast of cane yield for each farm, given that farms are contracted to harvester operators and farms are allocated to the nearest siding.

$\lambda = [\lambda_1, \lambda_2, \lambda_3, \lambda_4]$, the weighting vector for the multicriteria objective where λ_1 is for daily bin supply to mill, λ_2 is for early bin supply to mill, λ_3 is for siding usage, and λ_4 is for loco and road-transport usage. Each $\lambda_1, \ldots, \lambda_4$ is a positive real number.

G = set of pairs of harvesters that cannot have overlapping days of cutting cane $\{i1, i2\} \in G \subset I$.

The harvester roster decision variable is defined as

$$x_{ij} = \begin{cases} 1 & \text{if harvester } i \in I \text{ is allocated} \\ & \text{to pattern } j \in J, \\ 0 & \text{otherwise.} \end{cases}$$

The analytical form of the objective function is

$$\begin{aligned} Z = \min\ & \lambda_1 \sum_{t \in T} \left(\sum_{k \in K} \left(\sum_{i \in I} b_{it} \sum_{j \in J} x_{ij} a_{jk} \right)^2 \right) \\ & + \lambda_2 \sum_{k \in K} \left(\sum_{i \in I} e_i \sum_{j \in J} x_{ij} a_{jk} \right)^2 \\ & + \lambda_3 \sum_{s \in S} \left(\sum_{k \in K} \left(\sum_{i \in I} b_i q_{is} \sum_{j \in J} x_{ij} a_{jk} \right)^2 \right) \\ & + \lambda_4 \sum_{r \in R} \left(\sum_{k \in K} \left(\sum_{i \in I} b_i p_{ir} \sum_{j \in J} x_{ij} a_{jk} \right)^2 \right). \end{aligned} \tag{1}$$

The harvester rostering constraints are as follows:

$$\sum_{j \in J} x_{ij} f_{ij} = 1 \quad \forall i \in I, \tag{2}$$

$$\sum_{j \in J} x_{ij} = 1 \quad \forall i \in I, \tag{3}$$

$$\sum_{j \in J} x_{i1j} a_{jk} + \sum_{j \in J} x_{i2j} a_{jk} \leq 1 \quad \forall k \in K, \{i1, i2\} \in G, \tag{4}$$

$$x_{ij} = 0 \text{ or } 1 \quad \forall i \in I, j \in J. \tag{5}$$

Constraint (2) ensures that a harvester is allocated a permissible pattern while (3) ensures that only one pattern is allocated to a harvester. The case in which two harvesters must not have overlapping cutting days is represented by constraint (4). This constraint can be incorporated into the objective function by creating a dummy siding for harvesters $\{i1, i2\} \in G$. Since the third component of the objective function tries to minimize the daily variability of siding usage, it will effectively force the two harvesters to have patterns with nonoverlapping days of cutting cane.

The Tabu Search

The tabu search applied is based on the establishment of moves to transform a roster into a neighboring one. We used two neighborhoods with the harvester rostering problem, as follows:

Neighborhood 1: Change pattern move. If $x_{ij} = 1$, then let $x_{ij} = 0$, $x_{ij^\#} = 1$ where $j \neq j^\#$, $f_{ij^\#} = 1$ and $i \in I$, $j, j^\# \in J$.

Neighborhood 2: Swap pattern move. If $x_{ij} = 1$ and $x_{i^\# j^\#} = 1$ where $i \neq i^\#$, $j \neq j^\#$, $f_{ij^\#} = 1$, $f_{i^\# j} = 1$ and $i, i^\# \in I$, $j, j^\# \in J$, then let $x_{ij} = 0$, $x_{ij^\#} = 1$, $x_{i^\# j} = 1$, $x_{i^\# j^\#} = 0$.

Given that a harvester has up to seven permissible patterns and that a large mill has about 100 harvesters, the size of neighborhood 1 is up to 600 possible moves and the size of neighborhood 2 is up to 4,950 (100*99/2) possible moves if all harvesters had common permissible patterns. The neighborhoods are complementary since changing the pattern of one harvester is more likely to have a big impact on the objective function, while swapping patterns between harvesters will work better when it is difficult to improve upon the current objective function value.

At every iteration of the tabu search, each of the possible moves in the two neighborhoods of the current roster is evaluated by obtaining an objective function value. The best move found is the one that produces the neighboring roster with the smallest objective function value without being a tabu move. This best nontabu move is selected to transform the current roster into the neighboring roster. The tabu search allows nonimproving moves since the search will become stuck in a local optimum, no matter the neighborhood used. Since nonimproving moves are allowed, the tabu status is required to prevent the search from cycling through a series of rosters. If a move from neighborhood 1 is accepted, the reverse and forward moves are both listed as tabu (that is, $x_{ij} = 1$ and $x_{ij^\#} = 1$ are listed as tabu). If the move was from neighborhood 2, a pattern swap between harvesters $i, i^\# \in I$ is listed as tabu. A move is listed as tabu if it is one of the L most recent moves accepted. For neighborhood 1, it was necessary to list both the forward and reverse moves as tabu. For example, listing only the reverse move as tabu allows a harvester to be allocated to a different roster pattern and then back to the original pattern within only a few iterations of the search. This means L would have to be considerably longer to prevent cycling (for example, $L = 500$). The value of L that produced the best overall harvester rosters (in terms of the objective function) could be found only through experimenting using different values. For the five mill regions (that implemented the rosters), the best value of L varied little. This was an important result as it ensured that the tabu search was robust when the mill planning staff needed to make changes to the roster data inputs. The best overall value of L found was 25. Having values as high as 500 did not have much impact on the final roster and did not significantly slow the search because it took very little time to check the tabu status compared to searching the neighborhoods. The tabu status was overridden if the move satisfied an aspiration criteria, which in this case provided a better roster than any found previously.

We intensified the search after a predefined number of iterations ϕ by replacing the current roster with the best found so far. By experimenting with ϕ for each of the five mill regions, we found that a value of 50 worked well all round. To diversify the search and improve the roster over a long CPU time (for example, more than 10 minutes), we found that a penalty search (Srivastava and Chen 1993) worked well. This meant that objective function (1) had an additional component:

$\beta^* y_{ij^\#}$ if the move was from neighborhood 1,

$\beta^* z_{ii^\#}$ if the move was from neighborhood 2,

where β is the penalty weight, $y_{ij^\#}$ is the number of times harvester $i \in I$ was moved to pattern $j^\# \in J$ (neighborhood 1), and $z_{ii^\#}$ is the number of times the roster patterns of harvesters $i \in I$ and $i^\# \in I$ were swapped (neighborhood 2). A large value of β caused diversification too early in the solution process when it would normally converge rapidly towards the optimal, while too small a value meant the penalty search had negligible effect on the final roster. For the five mill regions that implemented the rosters, a value of β between 1.0 and 5.0 provided the best rosters.

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D. W. Neville, Manager, Cane Supply, Mackay Sugar Co-operative Association Limited, Pleystowe, QLD 4741, Australia, writes: ". . . Mackay Sugar has been working with Dr. Andrew Higgins from CSIRO Tropical Agriculture and CRC for Sustainable Sugar Production on a participative research partnership to mathematically optimise harvesting rosters for our local industry.

"The desired outcomes from this research are to:

1. have a more balanced daily allotment to reduce harvesting and transport costs;

2. have a more constant daily cane supply to the mill to reduce the potential for expensive mill stoppages;

3. allow a better utilisation of infrastructure, including bin fleets, rail and road transport;

4. decrease capital expenditure; and
5. reduce the cost of developing rosters.

"We wish to confirm that the results of this research to date have been implemented at our four sugar mills for the 2000 season and we are continuing to work with Dr. Higgins to further enhance the outcomes and develop a PC based version of the optimisation model for the near future.

"We also believe this research has application to the wider sugar industry."