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SCHEDULING TECHNIQUES TO OPTIMISE SUGARCANE RAIL

TRANSPORT SYSTEMS

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ABSTRACT

In Australia, railway systems play a vital role in transporting the sugarcane crop from farms to mills. In this paper, a novel job shop approach is proposed to create a more efficient integrated harvesting and sugarcane transport scheduling system to reduce the cost of sugarcane transport. There are several benefits that can be attained by treating the train scheduling problem as a job shop problem. Job shop is generic and suitable for all trains scheduling problems. Job shop technique prevents operating two trains on one section at the same time because it considers that the section or the machine is unique. This technique is more promising to find better solutions in reasonable computation times.

Key Words: scheduling; rail transportation, sugar.

1. INTRODUCTION

Sugarcane transport is an important element in the raw sugar production system. Sugarcane is transported in specially designed wagons called cane bins. The efficiency of the transport system has a huge effect on the performance of the production system and on its overall costs. Some of the potential effects of sugarcane transport on the production system are stopping the supply of cane to mills and causing interruptions to the raw sugar production process; delaying the arrival of sugarcane to the mill, allowing it to deteriorate and causing a reduction in sugar quality; delaying the arrival of empty cane bins to harvesters causing the harvesters to wait for empty bins and increasing their costs; and increasing costs through inefficiencies in the sugarcane transport system itself through the need for higher levels of labour and larger numbers of locomotives and cane bins.

In Australia, the railway system can generally operate for 24 hours a day while the harvesting period is generally limited to about 12 hours in the day. The cane railway system performs two main tasks: delivering empty bins from the mill to the harvesters at sidings; and collecting the full bins of cane from harvesters and transporting them to the mill. From the perspective of the transport system, the mill serves the function of converting full bins into empty bins while the harvesters convert empty bins into full bins.

The sugarcane transport system is very complex and is based on a daily schedule, consisting of a set of locomotives runs, to satisfy the requirements of the mill and harvesters. Producing efficient schedules for sugarcane transport can reduce the cost and limit the negative effects that

this system can have on the raw sugar production system.

Many researchers have developed optimization models to improve the efficiency of railway and sugarcane transport systems. However, there is still considerable work that can be done in this field to develop new techniques to achieve further efficiency improvements and get optimal solutions for the sugarcane transport problem.

An automatic cane railway scheduling system (ACRSS) was developed at James Cook University in the 1970s (Abel et al. 1981). The main aim of ACRSS was producing daily schedules for locomotives runs. This software solved the railway scheduling problem by dividing the problem into two parts: a routing problem that produced locomotives runs and a sequencing problem to determine the locomotives run start times that satisfy the harvester and mill requirements. Further refinement of the solution was then undertaken by adding locomotive runs to produce a daily schedule to satisfy the objective function. This function considered issues such as the number of cane bins, the cane age, a non-interrupted supply of full bins to the mill and the capacity of the sidings.

ACRSS has since been upgraded to be more efficient and easy to use but it still has many limitations. This scheduler depends on iterative techniques which produce feasible but not optimal solutions. ACRSS doesn't include all sugarcane transport system constraints, e.g. locomotive passing constraints, having two harvesters at one siding, and different speeds and load limits on different sections of track. Time-consuming, manual modifications are required to the produced schedules.

This paper reviews recent work in sugarcane transport and presents the starting point for a new model designed to produce efficient schedules by solving the cane transport scheduling problem. The new model includes the requirements of all major elements of the cane transport system to reduce the overall cost and optimise the performance of the system.

2. PREVIOUS RESEARCH

Previous studies of the sugarcane transport problem have considered the integration between harvest and transport systems while others have concentrated on improvements to railway capacity and operations. These studies used many techniques to develop new models to reduce the total cost of the sugarcane transport system. Recent research in other transport systems has also provided advances that can be applied to sugarcane rail transport such as research related to a single track train scheduling problem.

Grimley and Horton (1997) proposed a mathematical model to reduce the total cost of the harvest and transport system using optimization techniques. They used mathematical programming and operations research techniques to get the best solutions based on the analysis of collected data. The two models were formulated by mixed integer programs and used AMPL modelling language and CPLEX solvers. The model did not prove practical for use by sugar mills and is not in use.

Everitt and Pinkney (1999) described an integrated set of tools to manage the performance of a cane transport scheduling system. This work was designed to achieve integration between a schedule simulation program (ACTSS), the automatic schedule generation program (ACRSS) and the cane transport operations management tool (TOTools).

Martin et al. (2002) proposed a new approach using Constraints Logic Programming (CLP) to solve cane railway scheduling problems. ECL^{i}PS^e is a Prolog language with extra features to be a suitable for the system. This technique produced daily schedules to minimize the number of locomotives and their runs, satisfy the constraints of the system such as siding

capacity and the characteristics of bins on a train.

Higgins et al. (2004a) developed a modelling framework to improve transport and harvesting efficiency via two case studies in the Plane Creek and Mourilyan districts in North Queensland. The development of a modelling framework depended on integration between the harvesting and transport sectors in the sugarcane industry. These activities were divided into the following models: 1. harvest group and farms location; 2. Harvest haul model; 3. Transport model. 4. Financial model. This study used some analytical methods and modelling techniques which are useful in evaluating and optimizing each model and its activities.

Higgins (2004) concentrated on the reduction of costs of harvesting sugar cane and transport by building a model for optimising siding use by harvesting groups. This model was able to achieve best utilization of rail capacity, reducing the movement of harvesters between the sidings, and achieving satisfaction and fairness for growers in their siding use. Meta-heuristic techniques such as tabu search were used in this research. This method is more efficient than other local search heuristics because it is flexible enough to treat any expected or unexpected changes of the data or constraints of the system annually.

Higgins et al. (2004b) designed models for three regions in Australia to produce optimal harvest schedules of sugarcane. These models depended on the coordination between growers, harvesters, and mills. They developed software which was used to help the implementation process. These models achieved an increase in profits for all three regions.

Higgins and Davies (2005) introduced a simulation model for the capacity of sugar cane transport systems in Australia. The transportation modelling divides into two main types: 1. static models where all variables are assessed and assumed such as the time which is spent between cutting and crushing cane, the demand of bins and locomotives, and the time spent waiting for empty bins at the farms; and 2. dynamic models that produce many schedules which are suitable for unexpected events in the transport system. This study found that the average time spent between cutting and crushing of cane, locomotive movements per day, and time spent waiting for bins decreased when the harvesting time increased.

Higgins and Laredo (2006) designed a framework including mathematical models for harvesting and transport sectors. They used P-Median and spatial clustering formulations to build these models. In this research, the coordination and the integration between the parts and components of these models achieved good results to reduce the overall cost of the system. They applied this research on the north-east coast of Australia as a case study. As a result they could reduce the number of sidings and harvesters by increasing the period of harvesting to 24 hours per day.

Kozan and Burdett (2005) developed a new methodology to measure the capacity of a railway system. This model can be used to ease the transport process and may be applicable to sugar cane transport. They assessed some factors or variables which have a significant effect on railway capability such as length and weight of trains, stopping rules for trains, and the distance between two stations. Also, in this paper they proposed a new definition and estimation of train travelling times between two points. This time has a huge impact on the railway capacity.

Burdett and Kozan (2006) extended their previous work in railway capacity. In this study, they developed techniques to estimate the capacity for different railways systems to improve the network performance.

Ariano et al. (2007) developed a branch and bound method to solve a train scheduling problem as a blocking job shop problem. The branch and bound method improved the solutions to be near optimal and decreased the computation times. This research used a discrete event optimisation model to increase the efficiency of solutions. Zhou and Zhong (2007) proposed a new model for solving a single track train scheduling problem. They used a

branch and bound method to reduce the total time of train trips. In this research, they solved the conflicting train problems through a single railway track.

Burdett and Kozan (2008) proposed a novel hybrid job shop approach to solve a train scheduling problem. In this paper, they designed a disjunctive graph model of train operations and used meta-heuristic techniques such as simulated annealing. This approach achieved good results for many objective criteria and improved the train movements. Burdett and Kozan (2009) developed a new constructive technique to solve train scheduling problems. They used a job shop approach to solve this problem. This solution depended on a disjunctive graph model and constructive solutions methods. This technique achieved better results than meta-heuristics techniques for different criteria such as minimizing a makespan objective. Liu and Kozan (2009) represented the train scheduling problem as a blocking parallel machine job shop scheduling problem. In this model, they solved the blocking problems in single and multiple railway tracks. They extended the classical disjunctive techniques and proposed a new heuristic method named the feasibility satisfaction procedure to solve this problem. The new technique treated many complex real situations in train crossing problems.

3. THE MODEL

In this paper, an innovative new model is described to solve the sugarcane transport scheduling problem. A job shop scheduling approach is used. The scheduling theory, especially the job shop scheduling type, is generic and suitable for railway operations scheduling problems. Branch and bound and other techniques will be used to organise and schedule the system operations. The mathematical model proposed is a binary integer programming formulation model.

The model defines the track sections as machines and the train activities as jobs. Each job (train activity) contains a number of operations determined by start time and processing time at each machine (section). Some machines (sections) contain several units (parallel track sections, including sidings). The locomotive trip from the mill to the sidings and back to the mill is called a run. Each locomotive can do several runs per day. The total time for all operations during a run is equal to the run time. The total run time per day is the total completion time. At this stage of the research, the main objective of this model is minimising the total completion time

The main model contains two main parts: the objective function and the constraints. This model is being formulated using binary integer programming. Most of the previous studies used constraint logic programming (Martin et al. 2001) or mixed integer programming (Lopez et al. 2006).

Notation

K   number of locomotives.

k,n   index of locomotives.

S   number of sections.

s index of sections; $s = 1, 2, 3, ...S.$

U   number of units of section s.

s^u index of unit unit u of section s ; u=1,2,……….U.

$$U = \begin{cases} 1, \text{ the sections } S_{1s} \text{ are } sin\,gle \text{ sections } ; s=1,2,3,...,S. \text{ (No collecting or delivering)} \\ \text{otherwise, the sections } s^u \text{ are sidings } ; 1 \le u \le U, 1 \le s \le S. \text{(There is collecting or delivering or both).} \end{cases}$$

r,a   index of operations in each job; r =1,2,…….R., a=1,2,…….R.

O   the total runs of each locomotive.

o,w   index of runs; o = 1, 2, 3,..., O.,w=1,2,…….O.

$t_{k^o s^u}$ start time of locomotive k in run o on the uth unit of section s.

f_{ks^u} finish time of locomotive k on the uth unit of section s.

g_{ks^u} processing time of locomotive k on the uth unit of section s.

$$X_{ks^u} = \begin{cases} 1, \text{ if locomotive k assigned to the } u^{th} \text{ unit of section s.} \\ 0, \text{ otherwise.} \end{cases}$$

$$q_{k^o rs^u} = \begin{cases} 1, \text{ if the operation r of locomotive k requires the } u^{th} \text{ unit of section s during run o.} \\ 0, \text{ otherwise.} \end{cases}$$

$$b_{kn^w as^u} = \begin{cases} 1, \text{ if locomotive k requires the } u^{th} \text{ unit of section s, but} \\ \quad \text{operation a of locomotive n scheduled at the same unit of the same section during run w.} \\ 0, \text{ otherwise.} \end{cases}$$

V   a big positive number.

$B_{c_{k^o s^u}}$ full bins collected from siding s by locomotive k during run o.

$B_{c_{k^o s^u d}}$ total full bins collected from siding s by loco k during run o at time d.

$B_{e_{k^o s^u}}$ empty bins delivered for siding s by locomotive k during run o .

$B_{e_{k^o s^u d}}$ total empty bins delivered for siding s by locomotive k during run o at time d.

A_s total allotment of siding s per day.

C_{K_e} capacity of locomotive k of empty bins .

C_{K_c} capacity of loco k of full bins .

d   index of time;d=1,2,3,...,D.

D   total work hours.

C_{s_s} siding capaity.

h_{S_s} harvesting rate at siding s.

h_M crushing rate at mill M.

The objective function

The main objective of this model is minimising the completion time for all runs in one day. Each locomotive has runs which contain some activities or operations. At this stage, it is assumed that the first operation for each run will start and finish at the 1st section. Equation (1) gets the total time for all runs and restricts the starting and finishing time for each run on the first section.

$$Min \sum_{k=1}^{K} \sum_{o=1}^{O} \sum_{r=1}^{R} \sum_{s=1}^{S} \sum_{u=1}^{U} q_{k^o rs^u} \ f_{k^o rs^u} - t_{k^o rs^u} \tag{1}$$

Rail operation constraints

Equations (2)-(11) explain the rail operation constraints responsible for passing all locomotives through the single track. These equations consider the delays during delivering and collecting the bins to and from sidings as follows:

Equation (2) shows the total duration for each operation as greater or equal to the processing time for that operation to any delays.

$$q_{k^o rs^u} (f_{k^o rs^u} - t_{k^o rs^u}) \geq g_{ks^u} \qquad \qquad \forall \ k,o,r,s,u. \tag{2}$$

Equation (3) shows that operation (r+1) of locomotive k cannot be processed before finishing operation r for locomotive k. (inbound locos).

$$(t_{k^o rs^u} + g_{ks^u}) q_{k^o rs^u} \leq q_{k^o r+1s^u} t_{k^o r+1s^u} - v(q_{k^o rs^u} - 1) \quad For \ k=1,2,3,..., \ K., o=1,2,3,..., \ O., r=1...,R-1., s \in S, u \in U. \tag{3}$$

Equation (4) shows that operation $(r)^{th}$ of locomotive k cannot be processed before finishing operation $(r+1)^{th}$ in locomotive k. (outbound locos).

$$q_{k^o r+1s^u} t_{k^o r+1s^u} \leq (1 - q_{k^o rs^u})(t_{k^o rs^u} + g_{ks^u}) - v q_{k^o rs^u} \quad For\ k = 1,2,3,...,\ K.,o = 1,2,3,...,\ O.,r = 1...,R-1., s \in S, u \in U. \tag{4}$$

Equation (5) shows that run $(o+1)^{th}$ of locomotive k cannot start before finishing run o^{th} of locomotive k. So, the finishing of the last operation in run o^{th} has to occur before the start time of the first operation in run $(o+1)^{th}$

$$\sum_{s=1}^{S} \sum_{u=1}^{U} (f_{k^o Rs^u}) q_{k^o R, s^u} \leq \sum_{s=1}^{S} \sum_{u=1}^{U} t_{k^{o+1},1,s^u}\ q_{k^{o+1},1,s^u} \quad For\ k = 1,2,3,...,\ K.,o = 1,2,3,...,\ O-1. \tag{5}$$

Equation (6) shows that each unit cannot process more than one locomotive at the same time.

$$\sum_{s=1}^{S} \sum_{u=1}^{U} X_{k^o s^u} = 1 \quad \forall\ k \in K, o \in O., s \in S. \tag{6}$$

In equation (7), each operation of any locomotive requires only one section s and one unit u in that section to be processed:

$$\sum_{s=1}^{S} \sum_{u=1}^{U} q_{k^o rs^u} = 1 \quad \forall k, o, r. \tag{7}$$

Equation (8) is a blocking condition. Operation r of locomotive k requires u^{th} unit of section s but the operation a of locomotive n is scheduled on the same units at the same section.

$$t_{k^o rs^u} \geq b_{kn^w as^u} t_{n^w as^u} \quad \forall k, n \in\ K\ and\ k \neq n,\ s \in S.\ u \in U.\ o, w \in o., r, a \in R. \tag{8}$$

Equation (9) ensures the non-negativity condition.

$$t_{k^o rs^u} \geq 0 \quad, g_{ks^u} \geq 0 \quad \forall\ k, o, s,\ u. \tag{9}$$

Locomotive constraints

Equations (10) and (11) are locomotive capacity constraints.

In equation (10), the number of empty bins delivered for all sidings during run o has to be less than or equal to the capacity of locomotive k.

$$\sum_{r}^{R} \sum_{s=1}^{S} \sum_{u=2}^{U} q_{k^o rs^u} B_{e_{k^o s^u d}} \leq C_{K_e} \quad \forall k, o, d. \tag{10}$$

In equation (11), the number of full bins collected from all sidings during run o has to be less than or equal to the capacity of locomotive k.

$$\sum_{r=1}^{R}\sum_{s=1}^{S}\sum_{u=2}^{U} q_{k^o rs^u} B_{c_{k^o s^u d}} \leq C_{K_c} \quad \forall k,o,d.$$

(11)

Bin constraints

Equations (12) and (13) show the relation between the total allotments for each siding and the number of full and empty bins delivered from or collected to each siding. These constraints will reduce the total number of bins used in the transport process.

In equation (12), the total number of empty bins delivered to siding s has to be equal to the allotment of this siding.

$$\sum_{k=1}^{K}\sum_{o=1}^{O}\sum_{r=1}^{R}\sum_{u=2}^{U}\sum_{d=1}^{D} q_{k^o rs^u} B_{e_{k^o s^u d}} = A_{s^u} \quad \forall \text{ s.}$$

(12)

In equation (13), the total number of full bins collected from siding s has to be equal to the allotment of this siding.

$$\sum_{k=1}^{K}\sum_{o=1}^{O}\sum_{r}^{R}\sum_{u=2}^{U}\sum_{d=1}^{D} q_{k^o rs^u} B_{c_{k^o s^u d}} = A_{s^u} \quad \forall \text{ s.}$$

(13)

Equation (14) satisfies the harvesters' empty bin requirements without delay. Each harvester needs a specific number of empty bins to collect the cane, and this number has to be reached in a specific time. This equation considers the number of delivered bins and the harvester rate to prevent any interruption in the harvesting process. Also, it considers the siding capacity to prevent the overflow of empty bins.

$$h_{S_s} \leq \sum_{k=1}^{K}\sum_{o=1}^{O}\sum_{u=2}^{U} B_{e_{k^o s^u d}} - d.h_{S_s} \leq C_{s_s} \quad \forall s, d.$$

(14)

Equation (15) satisfies the mill's full bin requirements without delay. This equation considers the number of full bins delivered and the crushing rate to prevent any interruption in milling processes. Also, it considers the capacity of the mill to prevent any overflow of full bins maintain the quality of cane.

$$h_{M} \leq \sum_{k=1}^{K}\sum_{o=1}^{O}\sum_{s=1}^{S}\sum_{u=2}^{U} B_{c_{k^o s^u d}} - d.h_{M} \leq C_{M} \quad \forall s, d.$$

(15)

CONCLUSION

The sugarcane railway operations are very complex and have a huge number of variables. The proposed scheduling model needs to be solved in a reasonable time, because of the dynamic nature of the system.

In the proposed model, the system constraints are divided into two main categories. Firstly, there are constraints related to the rail operations system. These constraints are very important to ease passing the locos without accidents or delays. Secondly, the constraints related to sugarcane operations such as locos, sidings, and mill capacity, harvesting rates, harvesting times, empty bins requirements, and full bins requirements. The sugarcane transport problem is being formulated by a binary integer programming approach.

The scheduling model has two major advantages: reactiveness and robustness. The main outputs of the model are efficient schedules for sugarcane transport systems to optimise the performance of the system. The objectives are minimising the costs of the sugarcane transport system, reducing the cane age, maximising the capacity of the railway system and ensuring a non-interrupted supply of full bins to the mill and empty bins to each harvester.

At this stage the initial formulation of the main model of sugarcane transport is finished but still needs to be implemented and improved. CPLEX software is being used to solve small size cases to validate and verify the model. Some constructive heuristic and meta-heuristic techniques will be developed to solve NP-Hard problems. Previous results of sugarcane transport scheduling will be used for validation and verification of the model.

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