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Optimization approaches for sugarcane harvest front programming and scheduling

Abordagens de otimização para a programação e sequenciamento das frentes de colheita de cana-de-açúcar

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Abstract: The production of sugar, ethanol, and electricity from sugarcane necessarily involves harvesting and transportation of raw materials, which are expensive and complex operations that affect industrial efficiency. The present study proposes optimization approaches to support programming and scheduling harvest front decisions, based on considering the representation of the lot sizing and scheduling problem on parallel machines with sequence-dependent setup times and costs, a modeling technique widely reported in the literature. We carried out real data experiments in order to verify the adequacy and consistency of this representation. The results show that the proposed approaches adequately represent the conceptual model studied and have great potential to reduce cost in real-life situations.

Keywords: Sugarcane harvesting planning; Programming and scheduling of harvest fronts; Lot sizing and scheduling; Mixed integer programming.

Resumo: *A produção de açúcar, álcool e energia elétrica a partir de cana-de-açúcar passa necessariamente pela colheita e transporte da matéria-prima, que são operações custosas, complexas e que interferem na eficiência industrial. Neste estudo, propõe-se abordagens de otimização para apoiar decisões de programação e sequenciamento das frentes de colheita inspiradas na representação do problema por meio de um modelo de dimensionamento e sequenciamento de lotes da produção em máquinas paralelas, com custos e tempos de setup dependentes da sequência, muito estudados na literatura. Para verificar a adequação e coerência dessa representação foram desenvolvidos vários experimentos com dados realistas. Os resultados obtidos mostram que as abordagens propostas representam apropriadamente o modelo conceitual estudado e têm grande potencial para redução de custos na prática.*

Palavras-chave: *Planejamento de colheita de cana-de-açúcar; Programação e sequenciamento de frentes de colheita; Dimensionamento e sequenciamento de lotes de produção; Programação inteira mista.*

1 Introduction

Sugarcane harvesting and transportation to bioenergy mills are key steps in the sugarcane production chain. Despite the great value added in the industrial stage, approximately 68% of production costs per ton of sugarcane are incurred during the agricultural production stage, according to the 2011/2012 harvest data (USP, 2012) collected from a sample of production mills in traditional areas in the South-Central region of Brazil. Harvesting and transportation determine the quality and regularity of sugarcane supply to the mills, which involves a complex logistics system. The efficient operation of this system requires the use of integrated planning and control tools combined with effective farming techniques to ensure advantageous production of sugar from sugarcane.

Some computational tools available in the market and in literature focus on the following planning and control models: sugarcane field reform planning (Barata, 1992; Higgins, 1999), crop planting planning (Sartori et al., 2001) harvesting planning (Barata, 1992; Grunow et al., 2007; Jena & Poggi, 2013) operational planning (Grunow et al., 2007; Jena & Poggi, 2013), and traffic control (Hahn & Ribeiro, 1999). However, there are few studies available in the

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literature addressing programming and scheduling of sugarcane harvest fronts (Junqueira, 2014).

Harvest front refers to the team that operates machinery or equipment such as the sugarcane harvesting machines (harvesters) and the forwarders (travel alongside the harvester to transport the load) and the teams that provide supply, equipment maintenance, and support to emergency services (fire truck) for sugarcane harvesting and the loading of the trailers for transportation. According to Souza (2001), harvest front can be considered as a production cell. Although there is a growing tendency for mechanization, harvesting can also be done by hand; thus harvesting can be classified into two categories: manual and mechanical harvesting. Sugarcane mills usually use various harvest fronts that operate in parallel but are scattered over the field to harvest the raw material in different harvest units called blocks (paddocks). The teams move across the harvest blocks, shifting from one block to another in order to operate in more than one block and meet the aggregate production plan goals.

Lotsizing and scheduling problems have been extensively reported in the literature, for example, the General Lot sizing and scheduling (GLSP), which takes sequence-dependent and sequence-independent setup times and costs into account (Fleischmann & Meyr, 1997; Drexl & Kimms, 1997; Meyr, 2000; Haase & Kimms, 2000; Araújo et al., 2007, 2008; Ferreira et al., 2009, 2010; Jans & Degraeve, 2008; Allahverdi et al., 2008; Toso et al., 2009; Clark et al., 2010). The GLSPPL, General Lot Sizing and Scheduling Problem for Parallel Production Lines, proposed by Meyr (2002) and also studied in Meyr and Mann (2013), allows for adequate representation of the lot sizing and scheduling problems of harvest fronts in sugarcane mills, as shown in the present study. Therefore, it is possible to support key decisions about this problem and address specific issues and gaps in the balance between harvesting and transportation capacity, and the impact of the harvest front shifts on harvesting capacity.

The present study proposes optimization approaches for the programming and scheduling of harvest fronts for a multiple period-planning horizon (e.g., weeks or months of in the harvest season), based on mixed integer programming models for GLSPPL to support decisions about harvesting, crop planting, and reform of harvest blocks. The present study was carried out with the collaboration of a logistics consulting firm, which had dealt with such issues before, and two mills (Companies A and B) located in the State of São Paulo, with typical features of companies in the sugar-energy sector.

The remainder of this paper is organized as follows. Section 2 discusses programming and scheduling problems of sugarcane harvest fronts; Section 3 introduces three approaches for the optimization of the problem based on GLSPPL. Section 4 presents the analysis of the results of several computational real data experiments conducted to verify the adequacy and consistency of these approaches. Finally, Section 5 presents some final considerations about this research and suggestions for future studies.

2 Programming and scheduling of sugarcane harvest fronts

2.1 Definitions and concepts

Dividing areas or units into harvest fronts enables maintaining an average capacity of sugarcane transportation to the mill as the harvest fronts move across the blocks to neighboring areas that were aggregated to be harvested in the same time period. Maintaining the average transportation capacity would be impossible if all the effort was focused on a single area (all harvest fronts operating in a single block) because there would be either a surplus of resources, when the single harvest front is too close to the mill, or lack of resources, when the single harvest front is too far from the mill.

The same way the distance or length of trips can affect transportation, the different characteristics of the harvest blocks in terms of production environment, declivity, and systematization, in combination with the sugarcane variety, can determine harvesting capacity, especially in the case of mechanical harvesting. One assumption made is that an effective harvesting planning can keep harvesting and transportation capacity constant during the harvest fronts shifts across the blocks in order to keep harvesting and transportation resources approximately constant during the harvest season.

According to this harvesting planning, sugarcane should be harvested at a proper time and maturity (peak maturity) to allow maximum sugar recovery from a particular crop variety to prevent or avoid quality problems. However, the uncontrolled pursuit of maximum sugar yield can create a peak demand for transportation and harvest equipment. Shortage of equipment in peak periods leads to inadequate supply of raw materials causing cost increase, affecting the mills (Piewthongngam et al., 2009).

Another variable associated with harvesting planning is sugarcane field reform. Once planted, a stand can be harvested several times, but successive harvests usually give decreasing yields due to growing techniques, soil fertility, harvest time, and crop variety. Thus, in order to maintain the mills supplied during the harvest season, part of the plantation should be replanted or "reformed", as called by this industry sector (Barata, 1992).

2.2 Conceptual model and analogy with GLSPPL

Operations such as harvesting and transportation can impact the supply of raw materials to the mill, which should be as regular as possible to prevent disruptions in the downstream supply. However, harvest fronts cannot remain in a single area during the whole season because the amount of sugarcane available in each block is limited. It is worth mentioning that the shift of the harvest fronts across the blocks reduces sugarcane production capacity. Therefore, harvesting and transportation operations are subject to production capacity variations inherent in each block; which can be controlled by scheduling the blocks to be harvested. Such variations can be different depending on the mill areas, for example, expansion areas tend to be larger and can be more easily mechanized than traditional areas.

The mill may also have greater influence on the process of scheduling harvest blocks to be followed by the harvest fronts, according to the level of upstream vertical integration or type of exploration contract (land leasing, partnership, or supplier). On the other hand, the time windows reduce the mill influence on the harvest block scheduling, which have to be followed considering the following factors: length of time of industrial use, crop age, risk of fire, risk of flooding, soil with low water holding capacity, and road traffic. Additionally, transportation of harvest workers and equipment maintenance can also determine specific geographic areas for harvesting operations (separation into sectors).

The model proposed in the present study, should, therefore, aim to minimize the shift of harvest fronts during the harvesting season meeting the supply goals, balancing harvesting and transportation capacity, following the time windows, and taking the assumptions of harvest block aggregation into account, when needed. The output data of this model should support the decisions about the harvest front shifts, guide the choice of variety type (early, mid-season and late varieties) to be planted in the blocks, and validate the size of the lot i.e., the amount required of harvesters and tractor trailers to perform the harvesting operations. Vinasse irrigation is also an important variable to be considered since harvesting should leave enough area for the application of this sub-product obtained from ethanol production.

In this case, a harvest front can be viewed as a production line. The items produced would be the harvest blocks, and the time spent on harvest front shifts would represent the sequence-dependent setup times of the production line. It is worth highlighting that models aimed at harvest planning based on GLSPPL were not found in literature.

2.3 Research gap

Analyzing the models related to sugarcane harvesting and transportation planning available in the literature, it was observed that although the studies carried out by Higgins (1999), Higgins & Muchow (2003), Higgins et al. (2004), Grunow et al. (2007), and Jena & Poggi (2013) address many aspects of the situation-problem using GAP – Generalized Atribution Problem, planting and harvesting are addressed without examining the harvest front shifts. The discussions are based on previous concepts of harvest fronts without considering harvest block scheduling, reduction in the production capacity due to the harvest front shifts, and the impact of these shifts on harvesting and transport capacity.

However, this planning was shown to have some unfeasible and impracticable conditions. Last minute renting of equipment to increase harvesting and transportation capacity have become increasingly unlikely because of the specificity and high cost of harvesting and transportation resources, such as sugarcane harvesters, forwarders and transportation trucks (*rodotrem* or road train: a truck and trailer combination).

Therefore, maximum sugar recovery, which was part of the aggregate production plan, and the sale of the products partially occur or do not occur at all. This type of disruption hinders the relationship between the production chain links incurring losses due reduced industrial efficiency arising from the lower raw material quality and poor marketing strategies, especially in terms of potential markets.

Thus, there is a research gap characterized by the lack of an optimization approach addressing the harvest front scheduling aimed at managing the supply to the mill, growing techniques, harvesting and transportation capacity, which can guide the choice of variety type, and the size of the lot (the amount required of harvesters and tractor trailers). This issue is based on the needs of mills located in the south central part of Brazil, i.e., production units with self-managing harvesting and transportation structures, as well as tendency to mechanical harvesting and to form large conglomerates.

3 Optimization approaches development

To perform the modeling of the problem proposed, the GLSPPL was modified to represent the scheduling of sugarcane harvest fronts; it was used the GLSPPL with conservation of setup state, based on the studies conducted by Meyr (2002) and Meyr & Mann (2013), in which the products *j* would be the harvest blocks, and the production lines *l* would be the harvest fronts.

Three models are presented in this section. Model 1 is the basic model proposed in the present study. Models 1A and 1B are variations of the first model, i.e., they are strategies for finding good feasible solutions within acceptable computational times for large-scale problems. Model 1, which is more restrictive and within this context, looks for a solution that finds the best harvest time to maximize the yield from the block harvested within a certain time window. In addition, in order to consider the time lost due to the harvest front shifts (setup time), Model 1 includes constraints that do not include the setup time in the harvest capacity of the harvest front.

Since including the setup time (time spent on harvest front shifts) usually makes the solution of lot sizing problems more difficult (Maes et al., 1991), Model 1A does not consider the capacity loss due to the harvest front shifts in the harvesting capacity constraint, but it seeks to minimize the time lost in the objective function. Thus, the model does not consider the best harvest window, searching for a solution to the other constraints. Model 1B minimizes the costs of grinding losses and losses associated with the raw material left unharvested in the fields; both are constraints in models 1 and 1A. In model 1 B, the time spent on harvest front shifts is used in the harvesting capacity considering slack variables in some constraints that are penalized in the objective function. The advantage of this model is that it always have a trivial feasible initial solution, i.e., do not harvest anything and pay all the costs incurred by grinding loss and sugarcane left unharvested.

Table 1 shows the indices and the sets included in the models, and Table 2 shows the parameters involved. The decision variables are similar to those used by Meyr (2002) and are shown in Table 3.

3.1 Model 1: best harvest time

The objective function of Model 1 takes into account the decision maker's preference to harvest a certain block *j* in the macro-period *t* (γ_{jt}) that belongs to the time window, i.e.,$(j,t) \in Bs_{jt}$. Table 4 shows the factors influencing the determination of the weighting factor γ_{jt}. The first group of factors considers the following: the fact that sugarcane is already planted, the variety cycle, and the harvest period (or planting period) of the last harvest season. For each situation, the cells represent the period in which the time window is open. The second group of factors, on the other hand, would be added to the value of the first group that is within the time window, and it consists of the risk of fire, risk of flooding, presence of sandy soil, and access by paved roads and by dirt roads (clay). It is important to highlight that months 1, 2, 3, and 12 are not shown in Table 4 because they are not typical harvest months in the South-Central region of Brazil.

For example, row 1 represents an area planted with early maturing variety sugarcane, in which the last time of cutting was performed according to the schedule; it obtains score 5 to harvest in months 4 and 5 and score 4 to harvest in month 6 to reduce the risk of harvesting outside the schedule. In this case, the adequate sugarcane field age for cutting is 12 months, within the range of the variety cycle, indicating balance between growing techniques and harvesting operations in the previous season. Row 10 in Table 4 shows that an area where sugarcane had not been planted yet and where there are no aggravating factors, obtains score 5 for any harvest period. If there is risk of fire (first row of aggravating factors) in the first two months, it would obtain score 7 and score 3 in the last four months, representing an encouragement to harvest in the months where there is reduced risk and a discouragement to do so in the other months.

Table 1. Indices and sets of the models proposed.

Symbol	Definition
i, j	harvest block
m	type of harvesting belonging to set *M=(man,mec)*
l	harvest front
t	macro-period
S_t	set of micro-periods *s* belonging to the macro-period *t*
$S0_t$	set with the first micro-period *s* of period *t*
F_m	set of the harvest fronts *l* belonging to the type of harvesting *m*
Bl_{jl}	set of the blocks *j* that can be harvested by the harvest front *l*
Bs_{jt}	set of the blocks *j* that can be harvested in the macro-period *t*
V_j	set of the blocks *j* that can be irrigated with vinasse

Table 2. Model parameters.

Symbol	Definition
dem_{mt}	mill demand per type of harvesting m in the period t (tons)
p_j	production of block j (tons)
f_{jm}	area of block j that can be harvested with the type of harvesting m
vin_t	minimum area with vinasse to be left by the harvesting in the macro-period t
TCH_j	productivity of block j (tons per hectare)
fi_j	area of block j that allows the use of vinasse
col_{mj}	harvesting capacity of block j with the type of harvesting m (tons per hour)
Np	vehicle for equipment transportation (step-deck trailer)
Nm_l	harvesting machines (harvesters) of harvest front l
Ht_m	number of hours of machine operation per type of harvesting m
st_{ij}	time required for a harvest front to move from block i to j
K_t	harvest front capacity in period t (time)
$transp_{mj}$	transportation capacity of block j with the type of harvesting m (tons per hour)
Nt	transportation vehicle (transportation trucks)
Htt	number of hours worked in transportation
bm_{lj}	minimum area of block j to enable the shift of harvest front l (tons)
T	total number of macro-periods
F	total number of harvest fronts
B	total number of blocks

Table 3. Model decision variables.

Symbol	Definition
x_{ljs}	production of block j in the micro-period s by harvest front l (tons)
y_{ljs}	$\begin{cases}1, \text{ if harvest front } l \text{ is in the block } j \text{ in the micro-period } s\\ 0, \text{ otherwise}\end{cases}$
z_{lijs}	$\begin{cases}1, \text{ if harvest front } l \text{ moves from node } i \text{ to } j \text{ in the micro-period } s\\ 0, \text{ otherwise}\end{cases}$

Table 4. Weighting factor γ_{jt} for the objective function.

	Is sugarcane already planted?	**Cycle**	**Last cutting/ planting**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
1	X	Early maturing	Early-season	5	5	4					
2	X	Early maturing	Mid-season			5	4	3	2		
3	X	Early maturing	Late-season					4	3	3	2
4	X	Medium maturing	Early-season	2	3	4	5	5	4		
5	X	Medium maturing	Mid-season			4	5	5	4		
6	X	Medium maturing	Late-season				3	4	5	4	3
7	X	Late maturing	Early-season	0	1	1	1	1	4	5	4
8	X	Late maturing	Mid-season				2	3	4	5	5
9	X	Late maturing	Late-season						3	5	5
10				5	5	5	5	5	5	5	5
Aggravating factors		Risk of fire		2	2	1	0	-2	-2	-2	-2
		Risk of flooding		-2	-2	1	2	2	1	-2	-2
		Sandy soil		2	1	1	-2	-2	1	2	2
		Paved road		2	2	1	0	0	1	2	2
		Dirt road (clay)		-2	-2	1	2	2	1	-2	-2

It is worth mentioning that these values represent a suggestion for the classification of the blocks in terms of the best time to harvest, based on Companies A and B and on the experience of one of the authors, who has been working in logistics consulting firm for more than ten years. A multi-criteria analysis should be carried out by the mill's planning specialist and the agriculture team γ_{jt} taking into account the agronomic and logistical factors relevant to the mill studied. Different scenarios for the weighting of γ_{jt} can be investigated, considering other information that is not included in the model parameters and also the experience of these professionals in dealing with this problem.

Model 1 is described by:

$$Max \sum_{t=1}^{T} \sum_{l=1}^{F} \sum_{j=1}^{B} \sum_{s \in S_t} \gamma_{jt} x_{ljs} \tag{1}$$

Subjected to:

$$\sum_{l \in F_m} \sum_{j=1}^{B} \sum_{s \in S_t} x_{ljs} \geq dem_{mt} \qquad (t = 1, \dots, T),\ (m = man,\ mec) \tag{2}$$

$$\sum_{l \in F_m} \sum_{s=1}^{N} x_{ljs} \leq p_j f_{jm} \qquad (j = 1, \dots, B),\ (m = man,\ mec) \tag{3}$$

$$\sum_{m=man}^{mec} \sum_{l \in F_m} \sum_{j \in V_j} \sum_{s \in S_t} fi_j \frac{x_{ljs}}{TCH_j} \geq vin_t \qquad (t = 1, \dots, T) \tag{4}$$

$$\sum_{j=1}^{B} \sum_{s \in S_t} \frac{24}{col_{mj} Nm_l Ht_m} x_{ljs} + \sum_{i=1}^{B} \sum_{j=1}^{B} \sum_{s \in S_t} \frac{Nm_l}{Np} st_{ij} z_{lijs} \leq K_t \qquad (m = man,\ mec), \forall l \in F_m, (t = 1, \dots, T) \tag{5}$$

$$\sum_{m=man}^{mec} \sum_{l \in F_m} \sum_{j=1}^{B} \sum_{s \in S_t} \frac{24}{transp_{mj} NtHtt} x_{ljs} \leq K_t \qquad (t = 1, \dots, T) \tag{6}$$

$$x_{ljs} \leq \min\left(\frac{col_{mj} Nc_l Htm}{24}, \frac{transp_{mj} NtHtt}{24} \right) K_t y_{ljs} \qquad (m = man,\ mec), \forall l \in F_m, (j = 1, \dots, B), (t = 1, \dots, T), \forall s \in S_t \tag{7}$$

$$x_{ljs} \geq bm_{lj} \left(y_{ljs} - y_{ljs-1} \right) \qquad (l = 1, \dots, F), (j = 1, \dots, B), (s = 1, \dots, N) \tag{8}$$

$$\sum_{j \in \left(Bs_{jt} \cap Bl_{jl} \right)} y_{ljs} = 1 \qquad (l = 1, \dots, F), (t = 1, \dots, T), \forall s \in S_t \tag{9}$$

$$y_{lis-1} = \sum_{j=1}^{B} z_{lijs} \qquad (l = 1, \dots, F), (i = 1, \dots, B), (s = 2, \dots, N) \tag{10}$$

$$\sum_{i=1}^{B} z_{lijs} = y_{ljs} \qquad (l = 1, \dots, F), (j = 1, \dots, B), (s = 1, \dots, N) \tag{11}$$

$$y_{ljs-1} \geq y_{ljs} \qquad (l = 1, \dots, F), (j = 1, \dots, B), (t = 1, \dots, T), \forall s \in \left(S_t \setminus S0_t \right) \tag{12}$$

$$x_{ljs} \geq 0 \qquad (l = 1, \dots, F), (j = 1, \dots, B), (s = 1, \dots, N) \tag{13}$$

$$y_{ljs} \in \{0, 1\} \qquad (l = 1, \dots, F), (j = 1, \dots, B), (s = 1, \dots, N) \tag{14}$$

$$z_{lijs} \geq 0 \qquad (l = 1, \dots, F), (i = 1, \dots, B), (j = 1, \dots, B), (s = 1, \dots, N) \tag{15}$$

The objective function 1 maximizes the preference for harvesting the blocks at the best time within a predefined time window. Constraints 2 and 3 ensure mass balance by adjusting the production in the field with the mill demand. Constraints 2 are related to the mill demand for grinding, ensuring that the amount of raw material harvested and transported of a particular type of harvesting is larger than the amount of raw material demanded within in the period. Constraints 3 limit harvesting and transportation depending on the availability of raw material in the block, and thus harvesting and transportation are associated with the production in the field, considering the type of harvesting performed and the type of block. Constraints 4 determine the minimum area of vinasse that should be left by the harvesting in each macro-period t, considering the amount of area that can be irrigated in the block.

Constraints 5 and 6 consider the capacity of the harvesting and transportation resources. Constraints 5 relate the time spent with harvesting resources and the time spent transporting equipment during the block shifts with the total time available in the period. The resource productive time takes into account the yield potential of the block and the agronomic suitability for the harvesting in the period. The time spent transporting equipment takes into account the time spent on block shifts and the number of step-deck trailers available for these operations. Constraints 6 refer to the transportation resources, whose production potential is considered per block. In this case, the time spent on the harvest front shifts is not considered because during the shifts these resources can transport the production of the active areas or they are idle, and the mill consumes the sugarcane on the trucks.

Constraints 7 to 9 and combine the variables x_{ljs} and y_{ljs}. Constraints 7 ensure that when there is production by the harvest front in the block j in the micro-period s, the harvest front is positioned in the same place at the same time. However, in the opposite situation, when the front is not positioned in the same place at the same time, there will not be any production in the block. It should be highlighted that the upper-bond for x_{ljs} was considered the minimum value between harvesting and transportation capacity. It is expected that harvesting capacity is the most restrictive, unless the capacity of a harvest front is larger than that of the entire fleet. Constraints 8 are the minimum lot size constraints, and they define the minimum amount of raw material to be harvested. Constraints 9 ensure that the harvest front l is positioned only in one block j in the micro-period s. Through the parameter Bs_{jt}, these constraints require that harvesting takes place in blocks j allowed by the time windows, i.e., in the macro-periods t. Furthermore, through the parameter Bl_{jl}, these equations define the blocks j that a harvest front can harvest. This occurs if there is a need to separate some harvest fronts into sectors. It is important to mention that that $y_{ljs} = 0$ is previously fixed for the micro-periods s that are outside of the time window of block j and the harvest fronts l that are not able to harvest this block.

Constraints 10 and 11 define the harvest front shifts across the blocks through the variable z_{lijs}, according to the position of the harvest front in the micro-period s (y_{ljs}) and the previous micro-period s-1 (y_{lis-1}). These constraints are modifications to those proposed by Wolsey (1998) and Ferreira et al. (2012). Constraints 12 were proposed by Fleischmann & Meyr (1997). Although they are redundant (their removal will not affect obtaining an optimum feasible solution), they force the idle micro-periods to occur only at the end of each macro-period, eliminating symmetrically equivalent solutions. Constraints 13, 14, and 15 define the non-negative variables x_{ljs} and z_{lijs}, as well as the binary variable y_{ljs} (it should be noted that because of constraints 10 and 11, the variable z_{lijs} does not need not be defined as a binary variable in (15), according to Meyr (2002) and Ferreira et al. (2012)).

3.2 Model 1A: minimum shift of the harvest fronts

Due to the difficulties to solve Model 1, i.e., to find acceptable solutions to large-size problems, a simple modification was used to reduce the model complexity and obtain feasible solutions of acceptable quality within reasonable computational times. Maes et al. (1991) point out that considering setup times (time lost due to the harvest front shifts) in the capacity constraint, such as in constraints 5, makes it more difficult to find a solution to the model. In Model 1A, constraints 5 would be inequalities 16 below:

$$\sum_{j=1}^{B}\sum_{s\in S_t}\frac{24}{col_{mj}Nm_l Htm}x_{ljs} \le K_t \quad (m = man,\ mec), \forall l \in F_m, (t = 1,\ldots,T) \qquad (16)$$

However, because the setup time is no longer considered in the model with this modification, the objective function is changed to Equation 17 in order to minimize the setup time of the harvest fronts; it would then be:

$$Min \sum_{l=1}^{F}\sum_{i=1}^{B}\sum_{j=1}^{B}\sum_{s\in S_t} Nm_l st_{ij} z_{lijs} \qquad (17)$$

It is important to highlight that in this case the number of step-deck trailers Np can be excluded because it is a constant.

3.3 Model 1B: minimum costs of harvest front shifts, grinding losses, and raw material left unharvested

In Model 1, the important decision makers' goals, such as the balance between raw material supply and industry grinding, are incorporated into the model constraints. Given the difficulties to solve Model 1, Model 1B may be considered as a simple variation of Model 1, in which slack variables were inserted into the production and demand constraints, and these variables were penalized in the objective function based on their unit cost. Therefore, while Model 1 seeks to find a feasible solution to the considered amount of harvesting and transportation resources, Model 1B analyzes the costs incurred due to production loss and to not meeting demand in potential infeasible solutions to Model 1, but which may be still acceptable for the decision-maker, depending on their magnitude. In Model 1B, costs of the harvest front shifts are present in the objective function, but it can be considered as having second-order effect, serving mainly as a tie breaker. The parameters that penalize these variables in the objective function are shown in Table 5, and the additional decision variables are constrained to be non-negative and are shown in Table 6.

From a demand point of view, if there is no production of raw material in the blocks or sufficient capacity for harvesting and transporting the raw material above the minimum grinding limit $mind_{mt}$ for the type of harvesting *m* in the period *t*, the demand will not be met, which is measured by the slack variable wm_{mt}. As previously mentioned, the lack of raw material causes major financial losses and great tension between the production chain links. One of the causes of the financial loss is the process restart cost, which can lead to an increase in steam consumption and efficiency loss in the mill. There will be even greater loss if the material deteriorates during this process. Another cause is the revenue loss for failing to process the raw material in a period of peak sugar content, when greater amount of sugar and alcohol can be extracted from a ton of raw material. If there are industrial workers that are hired only during the harvest period, an extra day of work means an extra day of pay. The hourly cost that relates all of these factors is *mo,* but it varies depending on the mill and determining it is not very simple due to the difficulty of defining and separating these factors. Determining this cost is therefore critical for using Model 1B.

There are also losses associated with the likeability of leaving sugarcane unharvested in a certain season to be harvested it the next season, which is known in Portuguese as "*bisar cana*" ("rerun" or "echo the sugarcane"). This loss is related to the slack variable wb_j of block *j*. In this case, in addition to this loss or postponement of gains, there may be "loss" of economies of scale due to reduction in the total amount of sugarcane processed per harvest season. This cost is represented by *bs*, and determining it is not as difficult as determining *mo* because factors such as the conversion of a tonne of sugarcane into final products, the market price for these products, the length of postponement (which can be up to one year), whether there are expected productivity gains or quality losses, and the minimum attractive rate of return must be taken into account.

The cost of transporting equipment was determined using the parameter *md*, which represents the operating cost of the step-deck trailer per kilometer, and thus the distance traveled between the blocks *i* and *j*, $dist_{ij}$ was used. This cost plays a secondary role in the objective function, serving primarily as a tie breaker.

As mentioned earlier, in order for the model to assess the impact of these costs, slack variables were added to the tonnes of sugarcane left unground and to the tons of raw material left unharvested (see Table 6). For each one of these parameters, there is a cost per hour or per ton (see Table 5), and in order for them to be considered, the objective function 1 is replaced with the Equation 18 below.

Table 5. Additional parameters involved.

Symbol	Definition
$[mind_{mt}, maxd_{mt}]$	Mill minimum and maximum demand per type of harvesting *m* in the period *t* (tons)
mo	parameter that considers the influence of loss of grinding capacity in the objective function (cost of a ton of sugarcane left unground)
bs	parameter that considers the influence of loss of raw material left in field in the objective function (cost of a ton of sugarcane left unharvested)
md	parameter that considers the influence of the distance traveled by the harvest front to move from one block to another in the objective function (cost of one km traveled in transporting equipment/machine)
$dist_{ij}$	Distance between blocks *i* and *j* (km)

Table 6. Additional decision variables.

Symbol	Definition
wm_{mt}	tonnes of sugarcane left unground of the type of harvesting *m* in the period *t*
wb_j	tonnes of raw material left unharvested in block *j*

$$Min\ mo\sum_{t=1}^{T} wm_{mt} + bs\sum_{j=1}^{B} wb_j + md\sum_{l=1}^{F}\sum_{j=1}^{B}\sum_{j=1}^{B} dist_{ij} z_{lij} \quad (18)$$

As for the constraint that limits minimum grinding, the slack variable replaces the constraints 2 with the constraints 19 and 20. It is worth mentioning that (19) should not be an equality constraint because if sugarcane grinding reached the maximum level, the slack variable would have to be negative.

$$\sum_{l\in F_m}\sum_{j=1}^{B}\sum_{s\in S_t} x_{ljs} + wm_{mt} \ge mind_{mt} \quad (t=1,\ldots,T),\ (m=man,\ mec) \quad (19)$$

$$\sum_{l\in F_m}\sum_{j=1}^{B}\sum_{s\in S_t} x_{ljs} \le maxd_{mt} \quad (t=1,\ldots,T),\ (m=man,\ mec) \quad (20)$$

Similarly, for the unharvested raw material, the slack variable is added replacing the inequalities 3 by Equations 21 that follow:

$$\sum_{l\in F_m}\sum_{s=1}^{N} x_{ljs} + wb_j = p_j f_{jm} \quad (j=1,\ldots,B),\ (m=man,\ mec) \quad (21)$$

Constraints 22 and 23 determine the non-negativity of the slack variables introduced.

$$wm_{mt} \ge 0 \quad (t=1,\ldots,T),\ (m=man,\ mec) \quad (22)$$

$$wb_j \ge 0 \quad (j=1,\ldots,B) \quad (23)$$

4 Computational experiments with test problems

This section describes a real data experiment (on a smaller scale) of the scheduling of sugarcane harvest fronts problem to verify the adequacy and consistency of the three models presented and discussed in the previous section. This example involves a number of variables and constraints that is small enough to allow finding the optimal solution to the three models using solver (CPLEX 12.5.1.0) within a relatively low computational time. Thus, some fictional data were also used in these experiments to facilitate model verification; please see Junqueira (2014) for more details.

4.1 Input data

This example represents the scheduling of two harvest fronts with self-management of a grinding mill with a capacity of 4,500 tons per day in a period of only 2 weeks; each week represents a macro-period. The total of 31,500 (dem_{mt}) tonnes per week was considered. The time available for the operation of the harvest fronts is 168 (K_t) hours per week. To supply grinding, there are 4 blocks with 17,000 (p_j) tonnes of raw materials to be harvested mechanically. The number of hours worked per resource is 15 (Ht_m) hours for a machine (manual and mechanical harvesting) and 16.6 (Htt) hours for the transportation trucks.

Table 7 shows harvest block data; mill's coordinates = (0,0). This table also shows the coordinates of the center of each block. It is important to highlight that in a real case, the distance between the mill and each block, easily determined, would be compared with, for example, the Euclidean distance between these points. The relationship between these two values would result in converting an Euclidean distance into the actual distance. Applying this relationship to any Euclidean distance, an estimate of the distance between the harvest blocks is obtained; which, it is rather inaccurate due to the number of possible combinations.

The transportation capacity of the mechanical harvesting ($transp_{mj}$) was obtained based on the load capacity and the length of trips of the transportation trucks, which comprises the travel times and the time spent in the field and at the mill. The mechanical harvesting capacity (col_{mj}) can be calculated using the harvester average speed, the block productivity, average length of the area harvested, row spacing, average time spent on maneuvering and repositioning the harvester and the forwarder, as shown in Table 8. Column R1 represents above-average yields, and column R2 represents average or below- average yields.

Table 9 shows the distance and travel times between the harvest blocks. To calculate the distances, an adjustment factor of 30% longer than the Euclidean distance was used. In real situations, this factor can be determined by comparing the radial distances (block - mill), measured by the mill and calculated using the Euclidean distance formula. On the other

Table 7. Harvest block parameters.

Blocks	Prod (t)	X'	Y'	Dist. (km)	Vel. (km/h)	Field (min)	Mill (min)	Cycle (h)	Loads	Tonnes (ton/load)	Transp. (ton/h)	Harv. (ton/h)
1	17.000	0	-15	15.0	30	35	25	2.0	2	32	32	30
2	17.000	-5	5	7.1	30	35	25	1.5	2	32	43	42
3	17.000	0	-5	5.0	20	35	25	1.5	2	32	43	42
4	17.000	-5	-15	15.8	30	35	25	2.1	2	32	31	30
Total	68.000	Average		10.7	28	35	25	1.8	2	32	37	36

Table 8. Harvest yield.

Parameters	R1	R2	Unit
Harvester average speed	4.5	5.0	km/h
Productivity	76.0	62.0	t/ha
Average length of the area harvested	0.60	0.30	Km
Spacing	1.5	1.5	M
Average time spent on maneuvering	1.5	2.0	min
t/h Total average	43.2	29.9	t/h/mach

Table 9. Distance and time spent on block shifts.

Blocks	distance in km-dist (*i*,*j*)				Time in hours-dist (*i*,*j*)			
	b1	b2	b3	b4	b1	b2	b3	b4
b1	0	27	13	7	0.0	2.0	1.6	1.4
b2	27	0	15	26	2.0	0.0	1.6	1.9
b3	13	15	0	15	1.6	1.6	0.0	1.6
b4	7	26	15	0	1.4	1.9	1.6	0.0

Table 10. Set of periods for harvesting operations and the best harvest time within the time window.

	Bs_{jt}		γ_{jt}	
	P1	P2	P1	P2
b1	1		5	
b2	1	1	5	4
b3	1	1	4	5
b4	1		5	

hand, to convert distance into time, the following were considered: time spent with the loading and unloading of the harvesters was 30 min, average speed of 40 km/h, and 85% of efficiency.

Table 10 shows the number of blocks where harvesting is allowed in the macro-periods (Bs_{jt}). It can be seen that block 2 (B2) cannot be harvested in the first period (P1), and block 4 cannot be harvested in the second period. Table 10 also shows the weight assigned to each harvest operation in the block in the macro-period (γ_{jt}), used only in Model 1, as described in section 3.1.

When using Model 1B (section 3.3), the costs of grinding losses, harvest front shifts, and sugarcane left unharvested must be introduced in the objective function. In the example, the cost of grinding loss (*mo)* was considered R$ 144,00 per ton (Brazilian Real). The cost of sugarcane left unharvested *bs* ("*cana bisada*") was considered R$ 5,00. The cost of harvest front shifts (*md)* was based on the diesel price per liter R$ 2,10 and a consumption of 5 km/l, resulting in R$ 0,42/km. To evaluate the cost of overestimating the resources required, the costs of sugarcane left unharvested were estimated as R$ 90,49 per hour and cost of transportation as R$ 61,46. To estimate these values, the capital cost and depreciation of the harvesters, tractor trailers, and transportation trucks were considered. The salary of these machines' operators and the truck drivers were also considered as costs. Please see Junqueira (2014) for more details of the costs and other input data of these test problems.

Models 1, 1A, and 1B were coded on GAMS 24.1.3 and run by CPLEX 12.5.1.0 (optimal solution). The experiments were performed on a PC with processor Intel Core i7-2600 CPU 8-Core 3.40GHz and 16GB memory. The experiments involved 185 constraints and 235 variables, of which 32 are discrete variables. Computing time to obtain an optimum solution was less than 0.5 seconds.

4.2 Analysis of Model 1

For Model 1, five experiments were performed to analyze the influences of parameters that indicate the best time to harvest within the time window (γ_{jt}), the time window for harvesting (Bs_{jt}), and the changes in types of harvesting in the areas (f_{jm}) and (F_m). There was a surplus of harvesting and transportation resources in the tests performed (10 harvesters and 11 transportation trucks.

Experiment 1.1 uses the time windows and the best harvest times within the time window, according to Table 10. The type of harvesting of the harvest front F1 is manual and of harvest front F2 is mechanical. The blocks B1 and B3 allow only manual harvesting, while the blocks B2 and B4 allow mechanical harvesting. In this case, it is expected that harvest fronts operate according to the adequate harvesting type within the time windows that do not allow the harvesting of blocks B1 and B4 in the second period. Moreover, the transportation and harvesting constraints should be respected according to the availability of these resources.

Graph (a) in Figure 1 shows the shifts of harvest fronts F1 and F2 in this experiment, which occurred as expected. The blocks B1 and B4, which cannot be harvested in the second period, were harvested first; and harvesting was performed in compliance with the type of harvesting allowed in each block. In this case, there was a surplus of harvesting and transportation resources since the blocks with lower harvestability and that were located at a greater distance were harvested simultaneously, followed by those that were closer and had good harvestability. Furthermore, the resource surplus enabled the harvest fronts to travel long distances between the blocks without hindering the supply, such as shifting from B4 to B2 (26km) instead of shifting from B1 to B4 (7km). It is worth mentioning that the shift from B4 to B1 would not be allowed by the time window and type of harvesting constraints. These constraints do not allow choosing another harvest time either. In this case, The value of the objective function was 316,750, which is equivalent to a score of 4.75 with production of 66,750 tonnes.

It is important to highlight that the higher the value of the objective function, the larger the amount of raw material harvested at the best time possible within the time window. The best time to harvest is represented by γ_{jt} (score 1-5), which was discussed in Section 3.1 and must be carefully determined by the mill's productivity planning specialist and the agriculture team.

In the experiments 1.2 and 1.3, the time windows were disregarded in the two periods considered, and γ_{jt} was modified. Table 11 shows the γ_{jt} values for both experiments. Since the type of harvesting is a very important factor for the harvest fronts and the blocks, the blocks to be harvested remain the same, but the harvest schedule is changed. In experiment 1.2, both shifts of F1 are allowed; however, in order to unsure the best harvest time, B1 should be harvested in the first period and B3 in the second period because they both have score 5 in those periods; otherwise, they would receive score 4 in both cases. On the other hand, the time of harvest does not influence the shifts of the harvest front F2 because the blocks have the same scores in the periods. However, when combined with the harvesting capacity, F2 processes B2 in less time due to its harvestability, and there is time left to process part of B4 in the first period. In the case of the experiment 1.1, this is not possible because the time window does not allow harvesting B4 in the first period. In experiment 1.3, it is expected to understand the effect of the change in the score of B4 in P2.

Graphs (b) and (c) in Figure 1 show the shifts of harvest fronts in experiments 1.2 and 1.3, respectively. As expected, in experiment 1.2, the harvest front moves from B2 to B4, which is different from the shift observed in experiment 1.1. The value of the objective function was 324,250, which is equivalent to an average score of 4.77 with production of 68,000 tonnes. These values are higher than those in the previous experiment because the harvest front processed larger amount of sugarcane (tons) due to the change in the time window, as previously mentioned.

On the other hand, it can be seen that in experiment 1.3 the shifts of the harvest front 2 changes again, harvesting B4 first, then B2, and returning to B4. In this case, since the shift it is not penalized and it seeks to maximize $\sum_{l=1}^{F}\sum_{j=1}^{B}\sum_{s\in S_t}\gamma_{jt}x_{ljs}$, the optimal solution indicated another shift to increase mill production

Table 11. γ_{jt} values for experiments 1.2 and 1.3.

	Exp. 1.2		**Exp. 1.3**	
	P1	**P2**	**P1**	**P2**
b1	5	4	5	4
b2	5	4	5	4
b3	4	5	4	5
b4	5	4	5	3

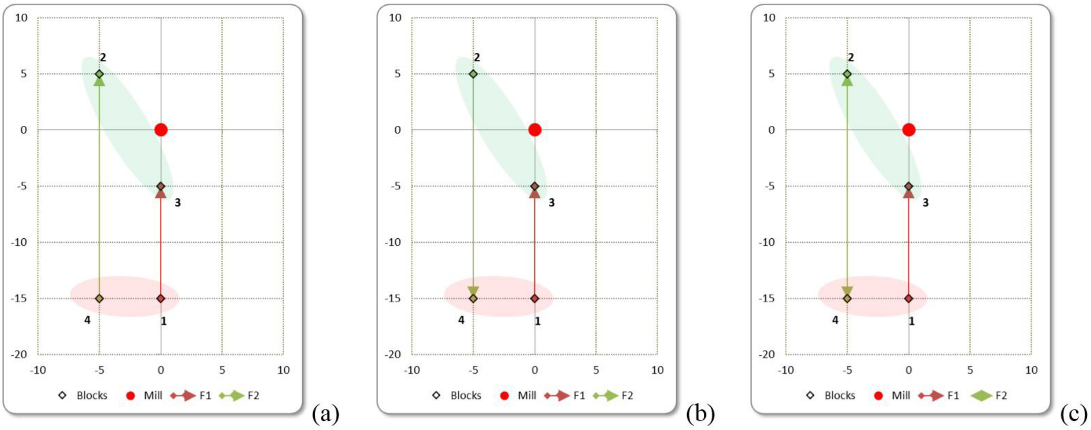

Figure 1. Harvest front shifts: (a) Experiment 1.1; (b) Experiment 1.2; (c) Experiment 1.3.

in those periods. However, although producing the same amount (68,000 tons) produced in the previous example, the value of the objective function reduced to 320,500, which is equivalent to an average score of 4.71. A lower absolute value of the objective function is expected because the B4 score in P2 is lower than that of experiment 1.2.

In Experiments 1.4 and 1.5, harvesting in B1 was not allowed in P1, and the γ_{jt} values of experiment 1.2 were kept equal. In experiment 1.5, it was determined that all blocks could be harvested mechanically, and therefore the two harvest fronts would be suitable for this type of harvesting. Graphs (a) and (b) in Figure 2 show the shifts of the harvest fronts in these two experiments.

As expected, comparing experiment 1.2 and experiment.4, it was observed a difference in the shifts of harvest front F1 because harvesting B1 in P1 was not allowed. There was also a reduction in the value of the objective function to 283,375, which is equivalent to a score of 4.27 with production of 66,375 tonnes. This reduction can be explained by the fact that such prohibition forced F1 to harvest B3 in P1, when it had score 4 instead of 5 in the previous experiment, and the fact that production was reduced due to the limitation of F1 in P2.

The harvest fronts had greater mobility in experiment 1.5 by being allowed to harvest any block. Therefore, graph (b) in Figure 2 shows that F2 harvested the areas of lower harvestability, while F1 harvested the most productive areas and could help F2 begin harvest operations in B4 and finish operations in B1. In this case, the value of the objective function was 323,000, which is equivalent to a score of 4.75. Since there was excess harvesting capacity, F1 could move more freely to harvest B3 with high score without leaving sugarcane unharvested.

4.3 Comparison of approaches

In this section the approaches related to Models 1, 1A, and 1B are compared. For Model 1A, two tests were performed based on experiments 1.4 and 1.5 to demonstrate the impact of the different assumptions underlying this model. To calculate the number of hours worked, the average time spent on shifts in Table 9 (b) was analyzed, which resulted in 1.7 hours. It was estimated that the harvest fronts would shift up to three times during the two-week period, which is equivalent to 1.5 shifts for each harvest front. Therefore, the harvesters' daily working time of would be reduced from 15 to 14.78 hours because there would be 5.1 hours spent on shifts in two weeks with 336 hours available.

As expected for both experiments, production was 63,000 tonnes in the two-week period, instead of 66 375 tonnes obtained in experiments 1.4 and 1.5 (section 4.2). This is due to the fact that Model 1 aims to harvest more sugarcane if there is sufficient harvesting and transportation capacity and raw material available. Model 1A, on the other hand, aims at the minimum amount of grinding. These different objective functions of models 1 and 1A also leads to another difference between the results of these models because the value of the objective function of Model 1 applied to experiment 1A is 267,750, which is lower than the values obtained in experiment 1.4 and 1.4' (283,375 for both). In addition to the changes in the amount of production and value of the objective function, the solution of experiment 1A.1 did not show major changes compared to that of the similar experiments in the previous section.

In the case of experiment 1A.2, unlike experiment 1.5 in which the objective was to obtain the highest amount of raw material at good harvest times, when the windows of time or the type of harvesting were

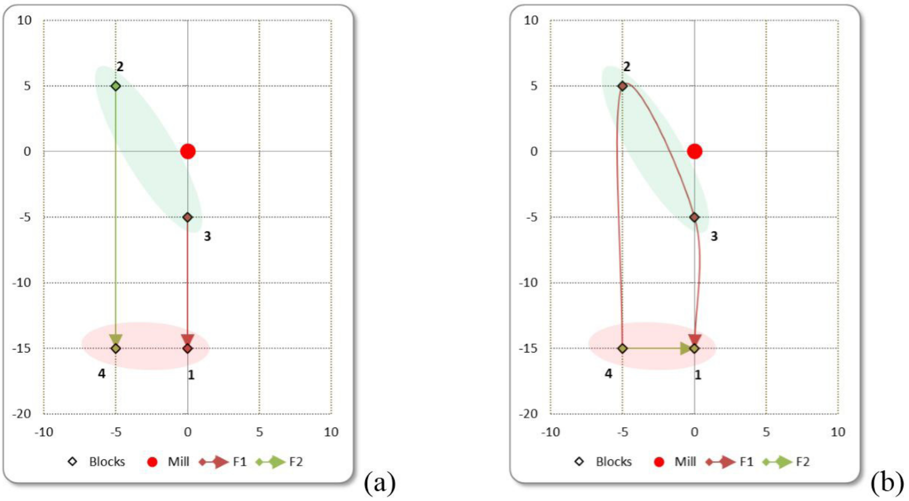

Figure 2. Harvest front shifts: (a) Experiment 1.4; (b) Experiment 1.5.

not restrictive, the number of shifts of the harvest fronts was the lowest possible. In experiment 1.5, on average, the time spent transporting each machine was 3.2 and 3.1 hours, respectively. However, the time spent on shifts by the harvest front with the largest number of shifts in each experiment was 5.1and 4.9 hours, respectively; and the time spent by the harvest front with the smallest number of shifts was1.4 hours in both experiments. It is worth mentioning that the assumption underlying Model 1A about the working hours was satisfied for the harvest fronts that shifted the most. However, in experiment 1A.2, the time spent on shifts was 1.5, on average, which is much less than the time considered in the recalculation of the hours worked.

Although Model 1A represents the problem with a lower degree of realism, the loss of capacity of the harvest fronts due to the shifts and also to the fact that they did not focus on harvesting the areas at the best harvest time, the other assumptions underlying this model were satisfied. Thus, it can be said that Model 1A has limitations when compared to Model 1, but it is more adequate to the problem situation than the other models found in the literature and generates a basic solution, which is, hypothetically, better than the solutions generated by the commercial software since it considers the shifts of the harvest fronts and harvesting and transportation capacity. Therefore, it is a good alternative to Model 1, when it cannot not find feasible solutions within acceptable time.

In the case of Model 1B (section 3.3), 11 experiments were carried out, and Model 1B was compared with Models 1 and 1A in two of these experiments. In addition, changes in the period available for harvesting (Bs_{jt}) and in the number of harvesters (Nc_l) and transportation trucks (Nt) were analyzed.

Experiment 1B.1 is similar to 1.4 and 1A.1, and experiment 1B.2 is similar to 1.5 and 1A.2. Their objective is to compare Model 1B with Models 1 and 1A. Table 12 compares the results presented in this section based on experiments 1.4 and 1.5 using the modifications of Model 1 proposed in this paper.

Unlike experiment 1A.1 and like experiment 1.4, experiment 1B.1 aimed at harvesting the maximum possible amount according to the harvesting and transportation resources because the unharvested sugarcane is penalized in the objective function. Therefore, the total value of the objective function of Model 1 is significantly higher than that obtained in experiment 1A.1 and slightly lower than that of experiment 1.4. However, the weighted average score of 1B.1 is slightly lower than that of the experiments of the other models. Similar behavior was observed in experiment 1B.2, but in this case it was possible to harvest the maximum available raw material since the harvesting resources were not restrictive.

4.4 Analysis of potential gains

This section discusses seven experiments (1B.3 - 1B.9), which are compared with each other to determine the gains obtained from operating without surplus of harvesting and transportation resources and also to identify the impact of inadequate time windows, resulting in the need for additional resources (Table 13). In experiment 1B.3, resource availability was changed to 10 harvesters and 9 transportation trucks, but the time window shown in Table 10 was kept the same. This experiment will serve as a basis for comparison with the other experiments in this section.

Experiments 1B.4 and 1B.5 demonstrate the behavior of Model 1B when the harvesters are made unavailable for operation. It is expected that since there is less availability of harvesters, the harvest front will make an effort to better exploit its harvest potential to prevent the lack of raw material, even if it is necessary to increase the number of shifts. If there is a reduction in the machinery availability but the resources are still sufficient to meet demand, this reduction represents gain of competitiveness advantage. This fine adjustment of capacity is one of the expected responses of this model.

In experiment 1B.4, 9 harvesters are available, and in experiment 1B.5, there are 8 harvesters available. It was observed the same harvest front shift behavior exhibited in experiments 1B.3 and 1B.4. However, in experiment 1B.4, there was no supply disruption and the operating cost of the harvest front shifts was lower (R$90,00) because there was one less harvester to be transported. In other words, in experiment 1B.3, there was one extra harvester, which corresponds to a cost of R$30,405 (2weeks*168h*R$90,49/h). In experiment 1B.5, there was a supply disruption of 3.576 tonnes, which resulted in an increase in the cost of the harvest front shifts and grinding loss

Table 12. Comparison between the results of the models proposed.

Experiment	Model	Production (t)	Obj. Func. of Model 1	Score
1.4	1	66.375	283.375	4.27
1A.1	1A	63.000	267.750	4.25
1B.1	1B	66.375	281.250	4.24
1.5	1	68.000	323.000	4.75
1A.2	1A	63.000	298.462	4.74
1B.2	1B	68.000	321.750	4.73

Table 13. Comparison between the results of the experiments.

Exp.	Number of harvesters	Number of tractor trailers	Cost of grinding loss (R$)	Cost of harvester idleness (R$)	Cost of tractor trailer idleness (R$)	B1 harvested in P2
1B.3	10	9	0	30,405	20,651	Yes
1B.4	9	9	0	0	20,651	Yes
1B.5	8	9	514,944	0	20,651	Yes
1B.6	9	8	0	0	0	Yes
1B.7	9	7	367,200	0	0	Yes
1B.8	9	9	385,300	0	0	No
1B.9	9	8	209,300	0	0	No

to R$514,944. In this example, however, it can be observed that the cost of grinding loss from operating with one less harvester is more than five times higher than that from operating with one extra harvester.

Experiments 1B.6 and 1B.7 exhibit the same behavior of Model 1B when the transportation trucks are made unavailable for operation, but with the same time availability for the blocks and based on 1B.4 experiment, which showed the most appropriate lot size (number of harvesters). Like in the case of the harvesters, it is expected that since there is less availability of tractor trailers for operation, the harvest front will make an effort to better exploit its harvest potential to prevent the lack of raw material, even if it is necessary to increase the number of shifts. In experiment 1B.6, 8 tractor trailers are available and in experiment 1B.7, there are 7tractor trailers available. It was observed the same harvest front shift behavior exhibited in experiments 1B.4 and 1B.6. However, in experiment 1B.6 there was no supply disruption due to operating with one less tractor trailer. In other words, in experiment 1B.4 there was one extra tractor trailer, which corresponds to a cost of R$ 20,650 (2weeks*168h*R$61,46/h). In experiment 1B.7, there was a supply disruption of 2.550 tonnes, which resulted in an increase in the cost of the harvest front shifts and grinding loss to R$367,200.

On the other hand, experiments 1B.8 and 1B.9 exhibit the same behavior of Model 1B when the time window is changed, prohibiting harvesting in block 1 in period 2 and removing one harvester in experiment 1B.8 and one tractor trailer in experiment 1B.9. In both cases, there is grinding loss, i.e., like in experiment 1B.5, these operations incur an extra cost of R$ 51,055. This cost can be mitigated if the planting of new areas is included in the scheduling of the harvest fronts, which takes into account the balance of the production capacity of harvesting and transportation resources.

5 Final considerations

This study proposed optimization approaches to solve the conceptual model described in section 2.2 of the programming and scheduling problem of sugarcane harvest fronts. Model 1 encompasses all relevant aspects of the conceptual model. Two variations of this model were also proposed to find a feasible solution to the problem requiring less computational effort since real problems are usually large-scale problems and usually it is not easy to find an optimal solution to them. Model 1A uses a simplification of harvesting capacity constraints, but Model 1B aims to obtain a good feasible solution within acceptable computational times by inserting a slack variable into the grinding constraint, penalizing grinding loss in the objective function.

The computational experiments performed were based on real data, but on a smaller scale to allow finding optimal solutions to the three models and verify their adequacy and consistency with the problem to be solved. Several experiments were performed to analyze the behavior of Model 1 and its two variations due to changes in the time window, the type of harvesting, and the number of harvesting and transportation resources. In all experiments, the models behaved as expected and were compared. In the variations of the Model 1, there was loss of opportunity in the search for the best harvest time in the macro-period within a certain time window; however, the variation in the weighted average score was not significant. Moreover, the search for the best time to harvest is a desirable feature but not mandatory for a scientific model since the time windows are followed. Based on the Model 1B, the economic impact of working with overestimated operating conditions and/or with grinding losses were also analyzed. This analysis showed that when there was grinding loss, the impact was greater than that created by resource surplus. However, there were costs of approximately R$30.000,00 in two weeks when there was one extra harvester and approximately R$20.000,00 when there was one extra tractor trailer. In other words, if the supply of raw materials is guaranteed, reducing idleness of harvesting and transportation resources will result in significant cost reductions. It was also demonstrated that it is possible to spare harvesters and tractor trailers if the time windows are "merged" keeping an average harvesting and transportation capacity potential during harvest periods.

Therefore, the proposed models represent the expected behavior and despite the limitations of the Models 1A and 1B in comparison to the Model 1, they are good alternatives to represent the problem and its characteristics allowing other strategies to facilitate finding a solution to the problem. Furthermore, the economic importance of reducing surplus of resources and searching for time windows that allow operating with a minimal amount of resources were also verified. It should be noted that this time widow change is possible mainly through the analysis of the balance between harvesting and transportation during the planting planning process, as discussed in the conceptual model of the problem studied. Other future research should address the application of these optimization approaches in real problems of Companies A and B and compare the solutions found with the solutions used by these companies to better evaluate the advantages and disadvantages of these approaches and validate them in real-life situations.

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