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Management of mechanized harvesting through operational modeling[1]

Gestão da colheita mecanizada por meio de modelagem operacional

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ABSTRACT - The activity of agricultural experimentation may require high budget and long periods of time for obtaining data. Due to production features, decision-making processes within agro-industrial mills that use sugarcane as raw material must be optimized. In this scenario, modeling operating systems that use embedded technology as agricultural automation enables the optimization of decision-making and influences operational performance and costs. This article presents a model for receiving and processing sugarcane based on its harvesting capacity, considering the harvestability index and the nominal capacity of the harvester. Sensitivity analysis enables the assessment of potential offenders and the reallocation of assets, thus optimizing resources and ensuring plant operation. This analysis also enables new possibilities, such as harvesting under different row spacings and harvesting simultaneously different rows.

Key words: Sugarcane harvest and loading. Modeling. Agricultural automation.

RESUMO - A atividade de experimentação agrícola pode exigir alto orçamento e longos períodos de tempo para obtenção de dados. Devido às características de produção, os processos decisórios em unidades agroindustriais que utilizam a cana-de-açúcar como matéria-prima devem ser otimizados. Nesse cenário, a modelagem de sistemas operacionais que utilizam tecnologia embarcada como automação agrícola possibilita a otimização da tomada de decisões e influencia o desempenho operacional e os custos. Este artigo apresenta um modelo de recebimento e processamento de cana-de-açúcar baseado em sua capacidade de colheita, considerando o índice de colheita e a capacidade nominal da colhedora. A análise de sensibilidade permite a avaliação de potenciais infratores e a realocação de ativos, otimizando recursos e garantindo a operação da planta. Essa análise também possibilita novas possibilidades, como colher em diferentes espaçamentos entre linhas e colheita simultânea de linhas.

Palavras-chave: Corte e carregamento de cana-de-açúcar, Modelagem, Automação agrícola.

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INTRODUCTION

When discussing agricultural experimentation, Côrrea *et al*. (2011) states that, for reaching reliable results, a research requires a series of experiments, which involves costs related to installation, maintenance, and data collection, as well as the time for performing them. Many times, installing plant experiments is not a viable option, thus requiring quick decision-making. To remedy situations such as these, one must accurately describe a real system, including the objectives and the interpretation of involved phenomena. However, such a simplification will only be possible upon a thorough understanding of the core concepts of operation of the system at stake.

Thus, models may be used to investigate a series of issues related to crop production, such as the crop behavior in its environmental context and its productive capacity under certain conditions, as well as to verify hypotheses, improve knowledge about processes, stimulate interdisciplinary integration, predict a system behavior, or even be used as a management tool for formulating a strategy. When compared to conventional experiments, models also show advantages in relation to installation, maintenance, and data collection costs (CORRÊA *et al*., 2011; MILAN; ROSA, 2015; SILVA, 2011).

Information on crop production costs is one of the most important tools for any productive activity, gaining increasing prominence in the management of agricultural companies – either in the analysis of production efficiency or in the study of specific production processes, thus indicating the success of a given company in its effort to produce. If, on the one hand, production costs have shown increasing relevance in rural administration, production efficiency, and strategic planning; on the other, the increasing adoption of information technology in agribusiness management gradually reduces the difficulties in estimating these costs, enabling data recording (BANCHI *et al*., 2019, 2020; BRAUNBECK; MAGALHÃES, 2014; INSTITUTO DE PESQUISA ECONÔMICA APLICADA, 2016; MAZZA, 2015; MILANEZ *et al*., 2020; SOUZA, 2012; RAMOS *et al*., 2016).

Associated with systems and processes modeling, data collected by Enterprise Resource planning (ERP), or integrated management system, can be evaluated under several approaches, such as costs, operational efficiencies, and resources dimensioning (LANÇONI *et al*., 2020; VILLAFUERTE *et al*., 2018).

According to Dias Neto (2015), agricultural automation consists in employing a set of tools that accelerate learning and are easily assimilated by employees working in the production, enabling real-time processes monitoring and ensuring sustainably and maximum productivity at a lower cost.

For Manzoni (2015), automation and management solution entail installing onboard computers with telemetry systems for controlling the machines involved in sugarcane cutting, loading, and transporting. Together with the back end and Portal, this method provides a management system for moveable assets and processes adequate to the operational reality of the sugar-energy sector production units.

When discussing the relevant features for obtaining the expected outcomes in agricultural automation, Dias Neto (2015) states that the involved equipment must present reliability and robustness, flexibility and extensibility; offer solution for different types of equipment; promote integration with precision agriculture devices; identify the situation according to operation in progress; collect production data; and develop productivity maps.

All this processed data can be transferred at different frequency ranges, such as through GPRS. The onboard computer is able to recognize the location of the equipment through a global positioning system (GPS) antenna installed into it (BÉRGAMO, 2020; MILANEZ *et al*., 2020).

MATERIALS AND METHODS

The sugarcane harvester operational performance was determined based on the capacity of its active components to process the raw material and on the field harvestability index (HI).

The HI can be used as a decision-making tool for the harvesting operations within each plot during or in subsequent harvests, enabling a better control in relation to its operational capacity, as well as to the planning and management of the required fleet to meet the plant needs.

The HI was calculated considering the basic operations of self-propelled harvesters and the parameters presented in Table 1.

The harvestability was evaluated as described in Table 2 and Table 3.

Table 2 shows values associated with operational safety, i.e. state in which the risk of injury to people or damage to property is reduced to or below an acceptable level.

Table 2 and Table 3 offer suggestions of harvestability index evaluation parameters, adjustable according to the experience of each professional responsible for harvesting in an agro-industrial unit. The ultimate goal is to apply the concept to formulate a harvesting strategy that enables the constant supply of the industrial plant.

Table 4 shows the set of variables and equations used for the modeling of cutting and loading operations.

The input data used in the model obtained for the cutting, loading, and transporting operations are shown in Table 5, Table 6, Table 7, Table 8, Table 9, and Table 10.

Input variables may be obtained through the use of embedded technology. These values may significantly differ due to the particularities of each

Table 1 - Harvestability index

Parameter	Evaluation criteria
Agricultural productivity	t ha^{-1}
Trace length	Distance traveled by the harvester without the need for maneuvers, expressed in linear meters
Terrain slope	expressed in slope percentage
Occurrence of stones and stumps	Visual or area history assessment
Occurrence of erosion	Visual or area history assessment
Occurrence of weeds	Visual or area history assessment
Terrain leveling	Visual or area history assessment
Cane lodging	Visual evaluation

Table 2 - Parameters for setting the harvester speed

Parameter	Observation	Score	Maximum speed km h^{-1}
Slope	Up to 8%	1	6.0
	Up to 12%	2	5.0
	Up to 14%	3	3.0
	Over 14%	4	2.5
Occurrence of stones and stumps	No occurrence	1	6.0
	Some occurrence	2	5.0
	High occurrence	3	3.0
	Severe occurrence	4	2.5
Occurrence of erosion	No occurrence	1	6.0
	Some occurrence	2	5.0
	High occurrence	3	3.0
	Severe occurrence	4	2.5

Table 3 - Harvestability index evaluation parameters

Parameter	Observation	Score	Impact on operational capacity
Occurrence of weeds	No infestation	1	No impact
	Some infestation	2	10.0%
	High infestation	3	30.0%
	Severe infestation	4	50.0%
Terrain leveling	Leveled	1	No impact
	Somewhat leveled	2	2.5%
	Unleveled	3	7.5%
Cane lodging	Upright	1	No impact
	Some lodged stalks	2	5.0%
	Most of the stalks lodged	3	50.0%
	All of the stalks lodged	4	70.0%

Table 4 - Variables used in the equations for the modeling of cutting, loading, and transporting operations

Variable	Acronym	Unit
Financial assumptions		
Opportunity cost	OC	% year
Fuel	Vfuel	R$ l^{-1}
Lubricants	Vlub	R$ l^{-1}
Equipment initial value	EIV	R$
Equipment lifespan	ELS	Years
Equipment residual value	ERV	%
Fill-ins	F	%
Absenteeism	A	%
Social charges	Soc	%
Wage	W	R$ month^{-1}
Implement initial value	IIV	R$
Implement lifespan	ILS	Years
Implement residual value	IRV	%
Operational consumption		
Fuel	Fuel	l h^{-1}
Lubricant	Lub	l h^{-1}
Implement lubricant	Lubimp	l h^{-1}
Maintenance	Mai	% EIV
Implement maintenance	Maiimp	% IIV
Operational assumptions		
Field productivity (according to tons of sugarcane per hectare)	TCH	t ha^{-1}
Trace length	TL	M
Spacing between rows	Sp	M
Rows harvested simultaneously	NL	amount
Corrected harvestability index	CHI	%
Nominal yield	NY	t h^{-1}
Harvester maximum speed	Vmax	km h^{-1}
Loading Capacity	Cload	T
Logistic times		
End-of-row maneuver	MT	seconds.maneuver^{-1}
Auxiliary maneuver	Maux	min day^{-1}
Refuelling displacement	Dref	min day^{-1}
Nonproductive hours	Hnon	min day^{-1}
Work shifts	WS	shifts.day^{-1}
Meal breaks	MS	min shift^{-1}
Shift change	SC	min shift^{-1}
Area change	AC	min day^{-1}
Empty displacement	Demp	Min
Loaded displacement	Dload	Min
Load transfer	Tload	Min

Continuation Table 4

Maintenance times		
Interval between field maintenance	IFM	h
Duration of field maintenance	DFM	Min
Interval of garage maintenance	IGM	h
Duration of garage maintenance	DGM	Min
Operational supply times		
Refueling interval	RI	h
Refueling duration	Dref	Min
Interval between lubrication	Ilub	h
Lubrication duration	Dlub	Min
Knife exchange interval	Ikni	h day^{-1}
Knife exchange duration	Dkni	min $change^{-1}$
Equipment cleaning	Ceq	min day^{-1}
Checklist	Check	min day^{-1}

Table 5 - Financial assumptions used in the mechanized harvesting system model

Variable	Unit	Cut	Load
Opportunity cost (OC)	% year	8.50%	
Fuel value (Vcomb)	R$ l^{-1}	2.90	
Lubricating value (Vlub)	R$ l^{-1}	12.70	
Equipment initial value (EIV)	R$	1,050,000	438,600
Equipment lifespan (ELS)	years	7	10
Equipment residual value (ERL)	%	25%	20%
Fill-ins (F)	%	16.7%	16.7%
Absenteeism (A)	%	1.5%	1.5%
Social charges (SC)	%	70.0%	70.0%
Wage (W)	R$ $month^{-1}$	2,200.00	2,000.00
Implement initial value (IIV)	R$		220,000
Implement lifespan (ILS)	years		10
Implement residual value (IRV)	%		10%

Table 6 - Operational consumption of mechanized harvesting system operations

Variable	Unit	Cut	Load
Fuel (Fuel)	l h^{-1}	35.00	9.50
Lubricant (Lub)	l h^{-1}	0.10	0.15
Implement lubricant (Lubimp)	l h^{-1}		0.05
Maintenance (Mai)	% EIV	30%	10%
Implement maintenance (Maiimp)	% IIV		10%

Table 7 - Operational assumptions for mechanized harvesting system operations

Variable	Unit	Cut	Load
Field productivity (TCH)	t ha^{-1}	76.46	
Trace length (TL)	m	500.00	
Spacing between rows (SBR)	m	1.50	
Rows harvested simultaneously (NL)	amount	1.00	
Corrected harvestability index (CHI)	%	19%	
Nominal yield (NY)	t h^{-1}	130.00	
Harvester maximum speed (Vmax)	km h^{-1}	6.00	
Loading Capacity (Cload)	t		19.00

Table 8 - Logistic times for mechanized harvesting system operations

Variable	Unit	Cut	Load
End-of-row maneuver (TM)	seconds.maneuver^{-1}	110	
Auxiliary maneuver (Maux)	min day^{-1}	44.0	
Refuelling displacement (Dref)	min day^{-1}	10.0	
Nonproductive hours (Hnon)	min day^{-1}	110.0	15.0
Work shifts (WS)	shifts.day^{-1}	3	3
Meal breaks (MB)	min shift^{-1}	30.0	30.0
Shift change (SC)	min shift^{-1}	12.0	12.0
Area change (AC)	min day^{-1}	35.0	34.0
Empty displacement (Demp)	min		9.0
Loaded displacement ($D_{load)}$	min		8.0
Load transfer (T_{load})	min		5.0

Table 9 - Maintenance times of mechanized harvesting system operations

Variable	Unit	Cut	Load
Interval between field maintenance (IFM)	h	15.00	24.00
Duration of field maintenance (DFM)	min	110	100
Interval of garage maintenance (IGM)	h	900.0	230.00
Duration of garage maintenance (DGM)	min	1.500	1.110

Table 10 - Operational supply times for mechanized harvesting system operations

Variable	Unit	Cut	Load
Refuelling interval (RI)	h	24.00	24.00
Refuelling displacement (Dref)	min	24.00	20.00
Interval between lubrication (Ilub)	h	24.00	24.00
Lubrication duration (Dlub)	min	10.00	30.00
Knife exchange interval (Ikni)	h day^{-1}	18.00	
Knife exchange duration (Dkni)	min change^{-1}	30.00	
Equipment cleaning (Ceq)	min day^{-1}	60.00	15.00
Checklist (Check)	min day^{-1}	21.00	21.00

bioenergy unit, so that each company must use data that represent its operational characteristics.

The time and movement values used in the simulation refer to data obtained by Solinftec® MAG 100R and MAG 300 onboard computers during the 2018/2019 harvest.

MAG 100 and MAG 300 are onboard computers integrated with the Solinftec® telemetry system, which possesses mechanical and electronic properties that enable operator–system interaction by the entry of data on operations/activities, information and alerts, and the monitoring of agricultural equipment. These computers offer the following features:

Tracking: identifying position through relationships between spots, by address (avenue, street, city, etc.), on the map, and by virtual fence; as well as the creation of rules for operational events.

Monitoring and control: assessing the condition of automobiles, buses, trucks, agricultural machinery, and other vehicles.

In addition to these, the MAG 300 allows you to:

Measure events: pressure at the base cut, engine rpm, running engine signal, running conveyor signal, running implements signal, soil copier system manual/automatic signal; hydraulic oil level signal; hour meter; GPS signals (speed, date, time, longitude, latitude); GPRS signal for data transfer;

Operational status: operating, maneuvering, and moving;

Data input: operator identification, notes, deactivation identification; maneuver identification, maintenance identification.

RESULTS AND DISCUSSION

The mechanized harvest model was validated by a performance test on a harvest front with four harvesters lasting 24 h. The Chi-square statistical test indicated that the values obtained from operational yield in the field and the model estimates agreed with each other, indicating that the model fits for the purpose at a significance level of 0.05 (DIAS NETO *et al.*, 2022).

Table 11 describes the proposed modeling for cutting, loading, and transporting operations.

Table 11 - Equations for modeling of cutting, loading, and transporting operations

Variable	Acronym	Unit	Formula	Equation
Results				
Daily milling	Mday	t day^{-1}	$M_{day} = M_{hour} * 24$	1
Effective harvest days	EHD	Day	$EHD = HD * AA$	2
Corrected yield	HCY	t h^{-1}	$HCY = \begin{cases} NY * (1 - IC), IC < 70\% \\ NY * 30\%, IC \geq 70\% \end{cases}$	3
Harvest logistics time	Tlogh	h day^{-1}	$T_{\log h} = WS * \left(\frac{MS + SC}{60}\right) + \frac{MA}{60}$	4
Logistic loading time	Tlogt	h day^{-1}	$T_{\log t} = WS * \left(\frac{MS + SC}{60}\right) + \frac{MA + Hnon}{60}$	5
Field maintenance time	FMT	h day^{-1}	$FMT = \frac{24 * DFM}{60 * IFM}$	6
Garage maintenance time	GMT	h day^{-1}	$GMT = \frac{24 * DGM}{60 * IGM}$	7
Maintenance time	Tmai	h day^{-1}	$T_{mai} = FTM + GMT$	8
Mechanical availability	Amec	%	$Amec = \left(1 - \frac{T_{mai}}{24}\right) * 100$	9
Refuelling time	Tref	h day^{-1}	$T_{ref} = \frac{24 * Dref}{60 * RI}$	10
Lubrication time	Tlub	h day^{-1}	$T_{\text{lub}} = \frac{24 * I\text{lub}}{60 * D\text{lub}}$	11
Knife exchange time	Tkni	h day^{-1}	$T_{kni} = \frac{24 * Dkni}{60 * Ikni}$	12
Harvester operational supply time	TOSH	h day^{-1}	$TSO_H = T_{kin} + T_{\text{lub}} + T_{ref} + \frac{Ceq + Check}{60}$	13
Loading operational supply time	TOSL	h day^{-1}	$TSO_L = T_{\text{lub}} + T_{ref} + \frac{Ceq + Check}{60}$	14

Continuation Table 11

Harvester engine hours	HEH	h	$HEH = 24 - \left(T_{\log h} T_{mai} + TOS\right)$	15
Loading engine hours	LEH	h	$LEL = 24 - \left(T_{\log t} + T_{mai} + TOS_t\right)$	16
Linear productivity	Plin	t m^{-1}	$Plin = \frac{TCH * Esp}{10.000}$	17
Operating speed	Sop	km h^{-1}	$Sop = \frac{HCY}{1.000 * Plin * NL}$	18
Harvested volume per row	HVR	t	$HVR = Plin * NL * TL$	19
Time trace length + Maneuver	TTLM	min	$TTLM = \frac{(60 * TL)}{(1000 * Sop)} + \frac{MT}{60}$	20
Harvested rows	Rhar	harvested rows day^{-1}	$Rhar = \frac{HEH - \frac{Maux + Dref + Hnon}{60}}{NL}$	21
End-of-row maneuver time	Term	h day^{-1}	$T_{erm} = \frac{Rhar * MT}{3.600}$	22
Total maneuver time	MTTOT	h day^{-1}	$MT_{tot} = T_{erm} + \frac{Maux + Dref + Hnon}{60}$	23
Loading distance	LD	M	$LD = \frac{Cload}{Plin * NL}$	24
Amount loading maneuvers	ALM	maneuver.load^{-1}	$ALM = 1 + \left(\frac{DCY}{TL}\right)$	25
Loading time	LT	Min	$LT = \left(\frac{\frac{LD}{1.000}}{Sop}\right) * 60 + \frac{ALM * MT}{60}$	26
Loading cycle total time	LCTT	Min	$LCTT = LCTT + D_{cmp} + D_{load} + T_{load}$	27
Loading cycles per day	LCD	cycles d^{-1}	$LCD = \frac{60 * LEH}{LTCT}$	28
Harvester operational yield	HOY	t day^{-1}	$HOY = \left(HEH - MT_{tot}\right) * \left(1.000 * Sop * Plin * NL\right)$	29
Loading operational yield	LOY	t day^{-1}	$LOY = CD * Cload$	30
Loading/harvester ratio	Ralh	Amount	$Ralh = \frac{Mor}{Lor}$	31
Harvester productive hours	HPH	h day^{-1}	$HPH = HEH - MT_{tot}$	32
Harvester use	Uh	h year^{-1}	$UH = EHD * HEH$	33
Loading use	Ul	h year^{-1}	$Ul = EHD * LEH$	34
Total harvester fuel consumption	Hfuelt	l year^{-1}	$Hfuelt = Uh * Fuel$	35
Total loading fuel consumption	Lfuelt	l year^{-1}	$Lfuelt = Ui * Fuel$	36
Harvester ton fuel consumption	Hfuel	l t^{-1}	$Hfuel = \frac{Hfuel}{HOY * EHD}$	37
Loading ton fuel consumption	Lfuel	l t^{-1}	$Lfuel = \frac{Lfuel}{LOY * EHD}$	38
Total harvester lubricant consumption	Hclubt	l year^{-1}	$Hc\mathrm{lub}t = Uh * Lub$	39
Total loading lubricant consumption	Lclubt	l year^{-1}	$Lc\mathrm{lub}t = Ui * Lub$	40
Total loading implement lubricant consumption	Liclubt	l year^{-1}	$Lic\,\mathrm{lub} = Uh * Lub$	41
Harvester ton lubricant consumption	Hclub	l t^{-1}	$Hc\,\mathrm{lub} = \frac{Hc\mathrm{lub}t}{HOY * EHD}$	42
Loading lubricant consumption	Lclub	l t^{-1}	$Lc\,\mathrm{lub} = \frac{Lc\mathrm{lub}t + Lic\mathrm{lub}t}{LOY * EHD}$	43
Harvester 24-hour effective yield	HDEY	t h^{-1}	$HDEY = \frac{HOY}{24}$	44

Continuation Table 11

Harvester engine effective yield per hour	HEEY	t h-1	$HEEY = \frac{HOY}{HEH}$	45
Harvester effective yield per productive hour	HPEY	t h-1	$HPEY = \frac{HOY}{HPH}$	46
Loading effective yield per productive hour	LPEY	t h-1	$LPEY = \frac{LOY}{24}$	47
Harvester fuel cost	Hfuelcost	R$ h-1	$Hfuel\cos t = HEEY * Hfuel * Vfuel$	48
Loading fuel cost	Lfuelcost	R$ h-1	$Lfuel\cos t = LPEY * Lfuel * Vfuel$	49
Harvester lubricant cost	Hlubcost	R$ h-1	$Ccust\,\mathrm{lub} = RECM * Hc\,\mathrm{lub} * V\,\mathrm{lub}$	50
Loading lubricant cost	Llubcost	R$ h-1	$L\,\mathrm{lub}\cos t = RET * Lc\,\mathrm{lub} * V\,\mathrm{lub}$	51
Harvester maintenance cost	Hmaicost	R$ h-1	$Hmai\cos t = \frac{EIV * Mai}{Uh}$	52
Loading maintenance cost	Lmaicost	R$ h-1	$Lmai\cos t = \frac{EIV * Mai}{Ui}$	53
Loading implement maintenance cost	Limaicost	R$ h-1	$Limai\cos t = \frac{EIV * Mai_{imp}}{Ui}$	54
Harvester operators cost	Hopercost	R$ h-1	$Hoper\cos t = \frac{W * (1 + Soc) * 13 * WS * (1 + A) * (1 + F)}{Uh}$	55
Loading operators cost	Lopercost	R$ h-1	$Loper\cos t = \frac{W * (1 + Soc) * 13 * WS * (1 + A) * (1 + F)}{Wi}$	56
Harvester depreciation	Depreh	R$ h-1	$Depreh = \frac{\left\{\left[EIV - \frac{EIV * ERV}{(1+OC)^{ELS}}\right] * \left[\frac{(1+OC)^{ELS} * OC}{(1+OC)^{ELS} - 1}\right]\right\} + \left\{\left[VII - \frac{IIV * IRV}{(1+OC)^{ILS}}\right] * \left[\frac{(1+OC)^{ILS} * OC}{(1+OC)^{ILS} - 1}\right]\right\}}{Uh}$	57
Loading depreciation	Deprel	R$ h-1	$Deprel = \frac{\left\{\left[EIV - \frac{EIV * ERV}{(1+TO^{ELS})}\right] * \left[\frac{(1+OC)^{ELS} * OC}{(1+OC)^{ELS} - 1}\right]\right\} + \left\{\left[VII - \frac{IIV * IRV}{(1+OC)^{ILS}}\right] * \left[\frac{(1+OC)^{ILS} * OC}{(1+OC)^{ILS} - 1}\right]\right\}}{Ui}$	58
Harvester total cost	Htotcost	R$ h-1	$Htot\cos t = Hfuel\cos t + H\,\mathrm{lub}\cos t + Hmai\cos t + Hoper\cos t + Depreh$	59
Loading total cost	Ltotcost	R$ h-1	$Ltot\cos t = Lfuel\cos t + L\,\mathrm{lub}\cos t + Lmai\cos t + Loper\cos t + Deprel$	60
No-stop tractor truck total cost	Nstrutotcost	R$ h-1	$Nstrutot\cos t = Nstfuel\cos t + Nst\,\mathrm{lub}\cos t + Nstmai\cos t + Nstoper\cos t + Nstdeprec\cos t$	61
Harvester ton total cost	Costharvest	R$.t-1	$Costharvest = \frac{Htot\cos t}{HEEY}$	62
Loading ton total cost	Costload	R$.t-1	$Cosload = \frac{TLtot\cos t}{RETD}$	63
Harvesters needs	Nhar	amount	$Nhar = \frac{M_{day}}{HOY}$	64
Loading needs	Nload	amount	$Nload = Nhar * Ralh$	65

As the management and mechanized operations with sugarcane account for a considerable percentage of production costs, and considering that these operations follow the rows and their paths, the efficiency and productivity of the equipment are proportional to the length and quantity of sugarcane per linear meter of the rows, especially in the harvest (BERNARDES; BELARDO, 2015). The harvester speed must be adjusted according to each area specificities, considering slope, type of soil and its microrelief, field length, plot size, and the estimated agricultural yield (BELARDO; ROSA; MAGALHÃES, 2015).

Sensitivity analysis seeks to predict results arising from changes in parameters or process activities; thus, it measures the degree of sensitivity of the process to a change, enabling the evaluation of the hypothetical impact of different types of change on the process as a whole, on a workflow, or on a specific activity, thus being useful for determining how a change can impact the operation. Thus, Figure 1 shows how NY and TCH variations act on the harvester operational performance. For NY, the values of 80, 90, 100, 110, 120, and 130 t h^{-1} were adopted; as for TCH, the values were 40, 50, 60, 70, 80, 90, 100, 110, and 120 t ha^{-1}.

Figure 1 allow us to conclude that:

While HCY is not reached, Sop remains the same as Smax; from this point, Sop will conform to HCY;

Variations in TCH have a direct impact in the harvester operational yield (HOY), being more significant while the HCY is not reached; after that, HOY will have marginal gains;

Considering that the average TCH expected for the 2020/21 crop is 76.3 t ha^{-1} for Brazil, 78.2 for the Center-South region, and 83.6 for São Paulo (COMPANHIA NACIONAL DE ABASTECIMENTO, 2020), and that the average age for the Center-South region is 3.6 (PROGRAMA DE EDUCAÇÃO CONTINUADA EM ECONOMIA E GESTÃO DE EMPRESAS, 2020), we may estimate that the productivity of about 30% of the harvest area will exceed 100 t ha^{-1}.

The quest for improving the operational performance of harvesters resulted in an alternative spacing that is currently adopted by some bioenergy units: the double alternate (0.90 m x 1.40 m), where two sugarcane rows are harvested simultaneously.

Figure 2 allows us to assess the impact of spacing changes.

By comparing Figure 2 with Figure 1, considering a 130 t h^{-1} NY, we verify:

a HOY greater than 60% when compared to 1.50 m spacing for TCH up to 90 t ha^{-1};

In the 100–120 t ha^{-1} range, for each 10 t ha^{-1} variation, HOY values are equal to 48.4%, 37.9%, and 28.9%, respectively. Figure 3 shows the comparison of both spacings regarding the impact on costs related to cutting, indicating that the difference between costs is greater as smaller the TCH. This result is obtained based on the maximum speed (Vmax), considered as 6.0 km h^{-1}, and the greater number of maneuvers in the 1.50 m spacing, reducing the harvester productive hours (HPH).

Figure 1 - Variations in Nominal yield (NY) and Field Productivity (TCH) and their impacts on Operating speed (Sop) and Harvester Corrected Yield (HCY) at 1.50 m spacing

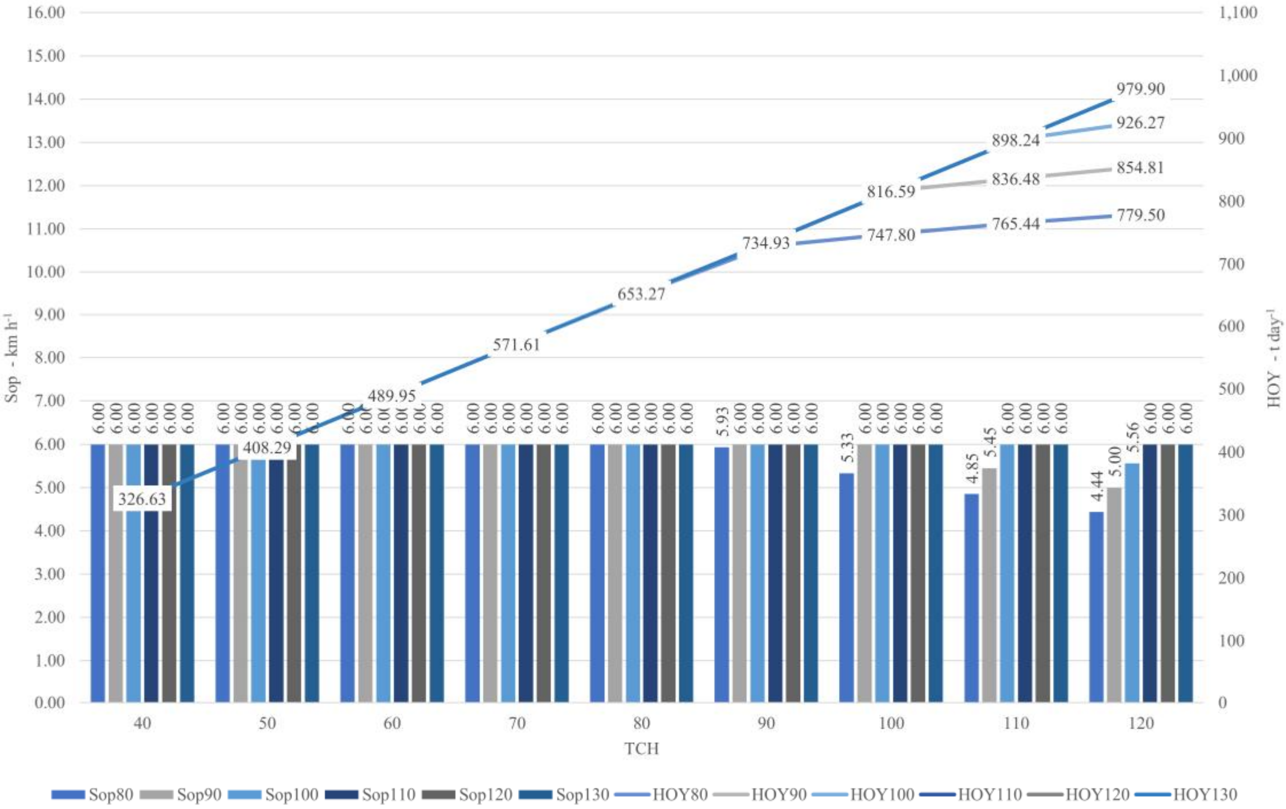


Figure 2 - Variations in Nominal yield (NY) and Field Productivity (TCH) and their impacts on Operating speed (Vop) and Harvester Corrected Yield (HCY) at 0.90 m x 1,40 spacing

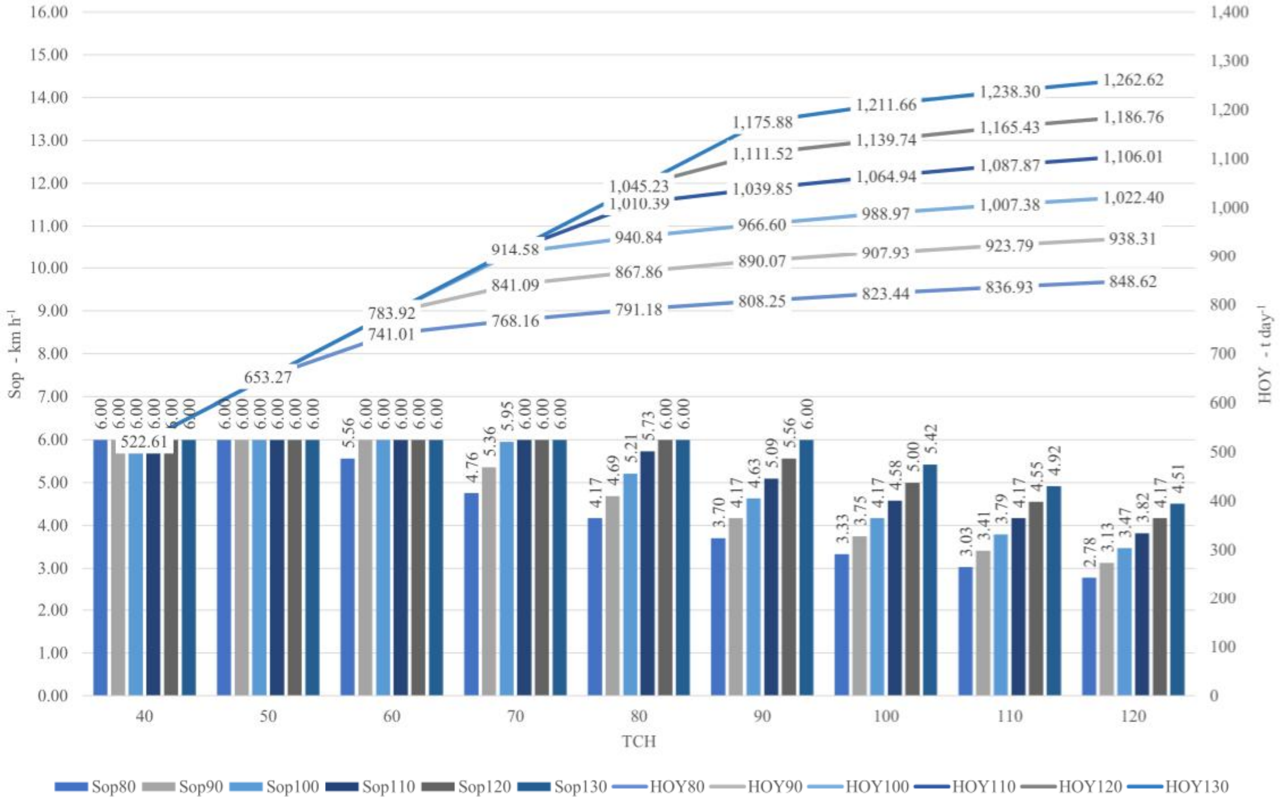
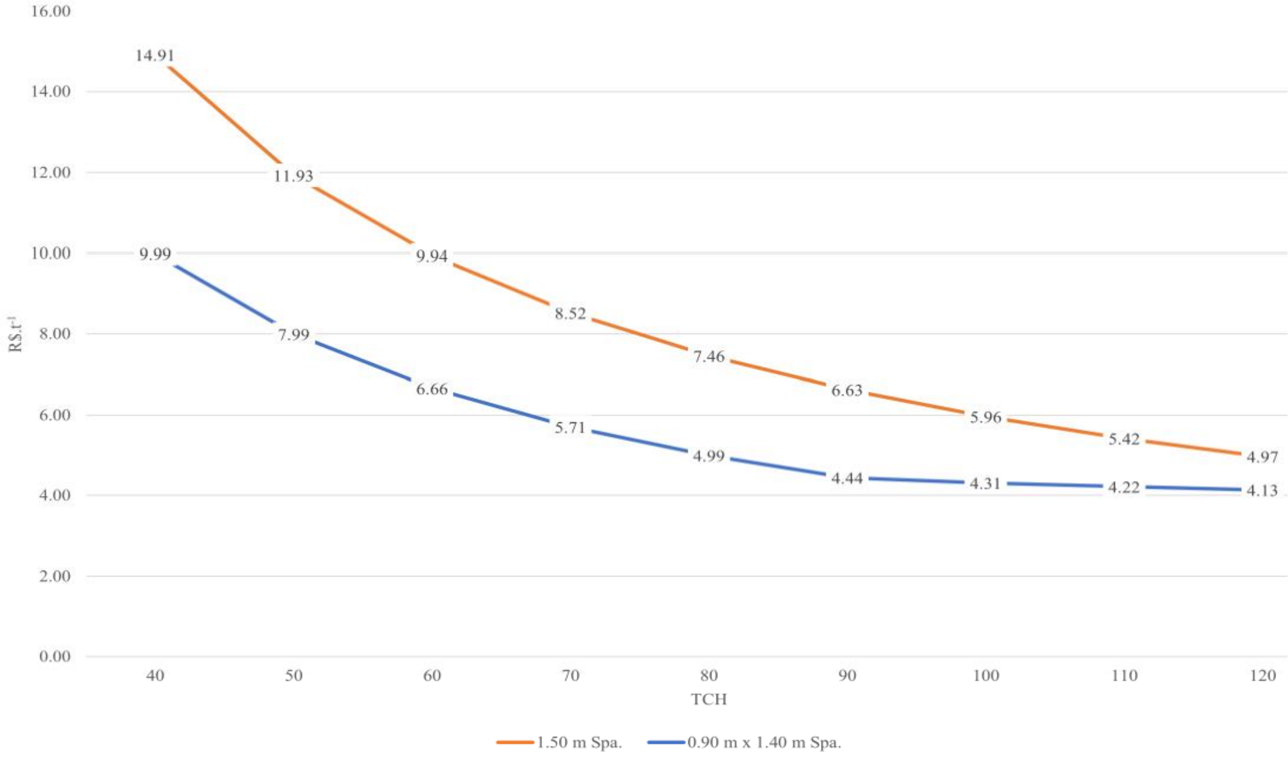


Figure 3 - Comparison of costs related to mechanized cutting of sugarcane in 1.50 m and 0.90 m x 1.40 m spacing



This work is not concerned with comparing advantages and disadvantages between 1.50 m and 0.90 m x 1.40 m spacings from the agronomic perspective, so that issues such as crop losses, impacts of water stress, and unfavorable production environments were not considered in the analysis.

The traffic control system (TCS) is intrinsically connected to the use of power steering devices, enabling the harvesting of two rows in a 1.50 m spacing – a possibility that has already been tested by some equipment manufacturers.

Similar to the analyses for the harvesting of a single row in 1.50 m spacing, Figure 4 presents the results obtained for the simultaneous harvesting of two rows.

The comparison between Figure 2 and Figure 4 indicates that the simultaneous dual-row harvesting in 1.50 m spacing has a better performance in areas with the same productivity (TCH). This result is explained by two aspects:

The harvester operating width, with 2.40 m for the double alternate and 3.0 m for the dual-row in 1.50 m spacing;

The number of end-of-row maneuvers, with 4,166.67 linear meters to be harvested per hectare by the double alternate and 3,333.33 linear meters by the dual-row in 1.50 m spacing. This difference results in less maneuvers and greater productive hours (HPC) – Equation 5.

Regarding HOY, dual-row simultaneous harvesting in 1.50 m spacing showed a performance 25% greater for TCH up to 70 t ha^{-1}; 15.9% for 80 t ha^{-1} TCH; and 5.8% for 90 t ha^{-1} TCH. For higher yields, the operational performance remained around 5%, limited by 130 t h^{-1} NY. The same behavior is observed for costs – Figure 5. The acquisition value of 150 thousand reais was added to both equipment.

Similar to mechanized sugarcane cutting operations, we may also analyze processes related to loading (traction). Figure 6 illustrates the impact of TCH on the loading performance expressed by loading operational yield (LOY) – Equation 30.

The smaller amount of time required to complete implement loading and the increase in TCH results in an increased ratio of the number of tractors required per harvester (Ralh) – Equation 26. Reducing loading time (LT) is not enough for diluting loading cycle total time (LCTT) – Equation 27, – so that more loading equipment will be necessary for meeting the harvester demand.

Figure 4 - Variations in Nominal yield (NY) and Field Productivity (TCH) and their impacts on Operating speed (Sop) and Harvester Corrected Yield (HCY) in the simultaneous harvesting of dual rows at 1.50 m spacing

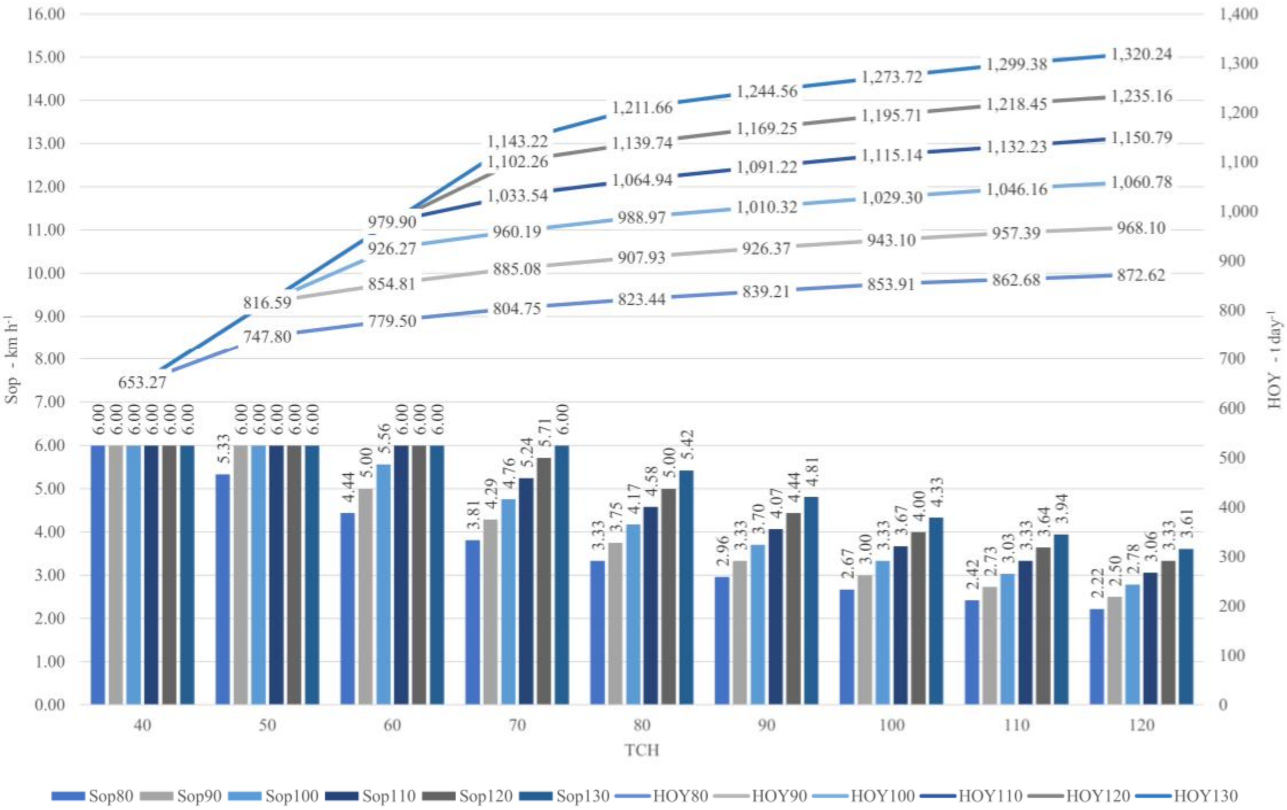


Figure 5 - Comparison of cost related to mechanized cutting of sugarcane in 1.50 m spacing, 0.90 m x 1.40 m spacing, dual-row simultaneous harvest in 1.50 m spacing

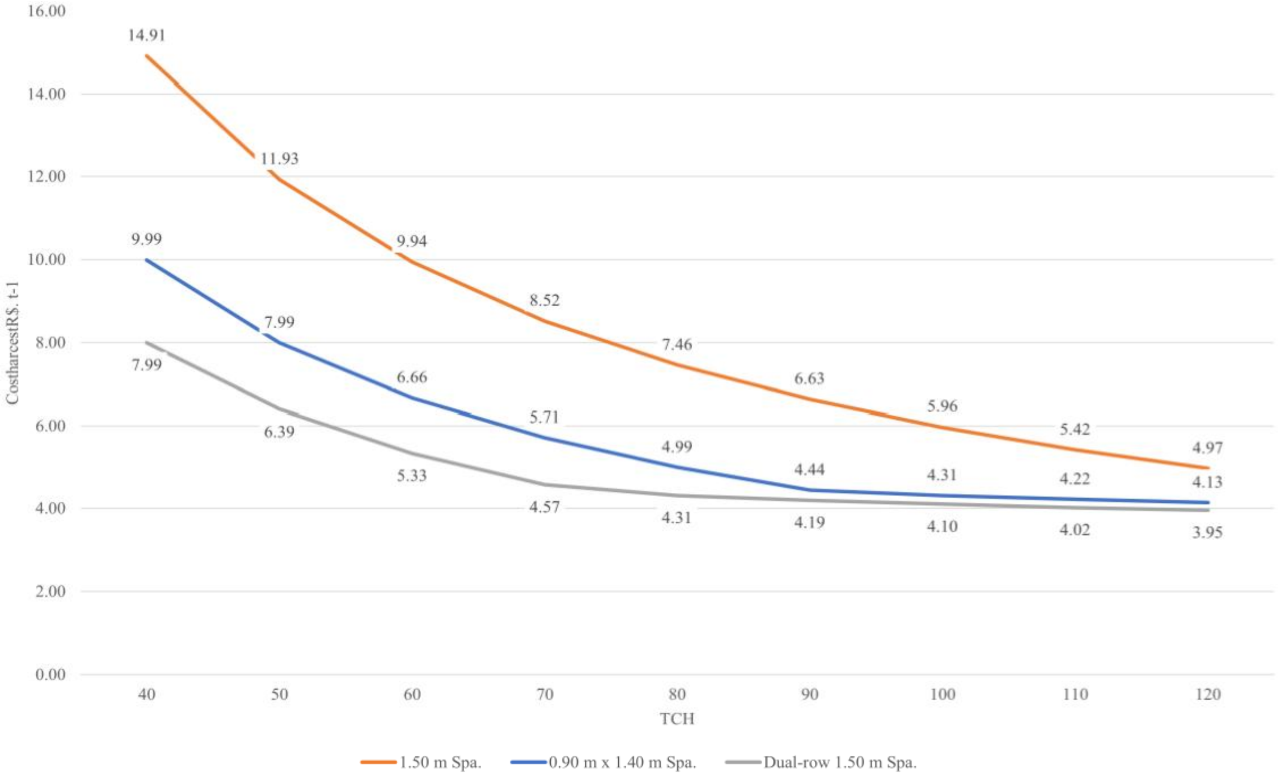
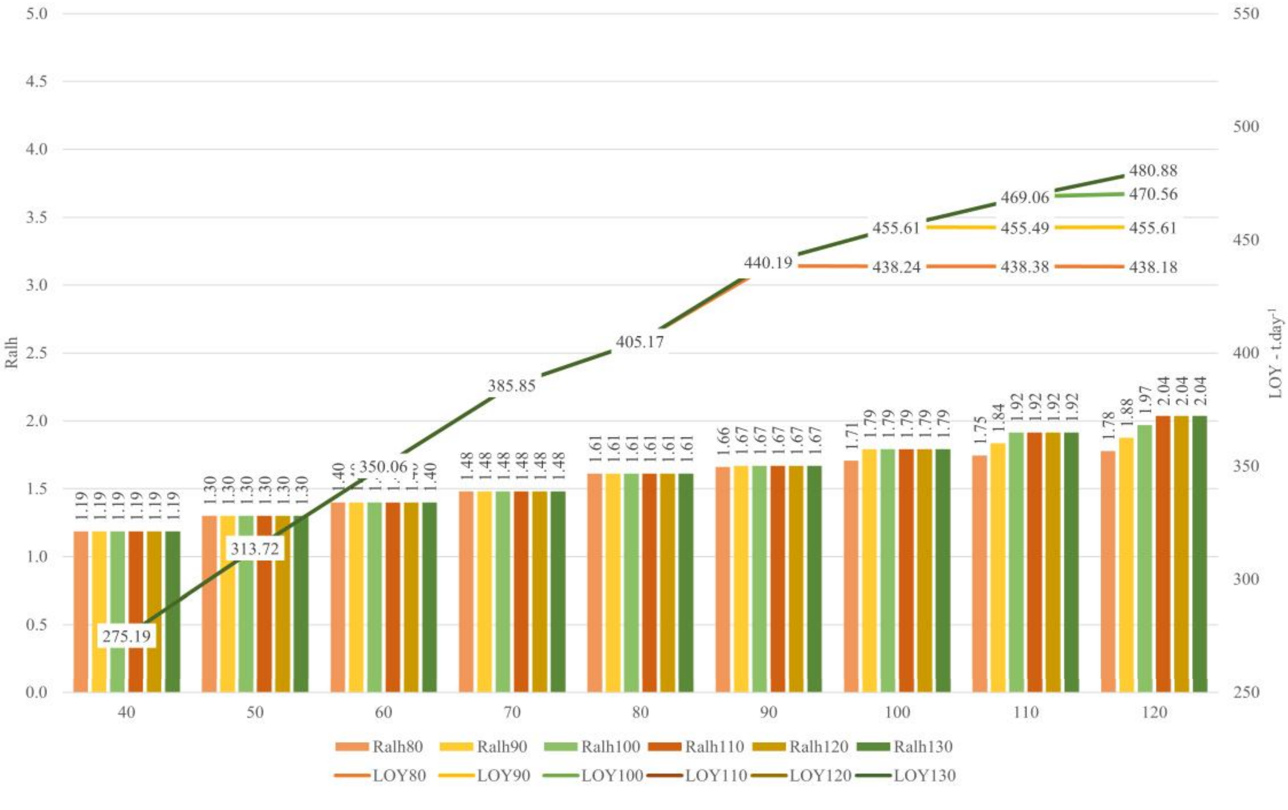


Figure 6 - Variations in Nominal Yield (NY) and Field Productivity (TCH) and its impacts on the loading–harvester ratio (Ralh) and loading operational yield (LOY) in 1.50 m spacing



The analysis of the loading operation performed by Figure 6 is better understood when considering the double alternate spacing, Figure 7; that is, the need for loading will increase as the harvester starts to operate in HCY conditions, for they will be limited to the LT.

Thus, as shown in Figure 8, operations performed in double alternate spacing and in dual-row simultaneous harvest in 1.50 m spacing will entail little performance variation of loading equipment.

Figure 9 presents the cost of the sugarcane loading operation considering a NY of 130 t h^{-1}. The results indicate significant differences for low yields, such as when comparing harvesting in one and two simultaneous rows in 1.50 m spacing in 40 t ha^{-1} TCH, with a reduction of 3.31 R\$.t^{-1} (32.1%). Thus, we may infer that cost differences decrease as TCH increases. We found that, up from 90 t ha^{-1}, costs related to loading are equivalent in both harvesting methods.

According to Bérgamo (2020), assets monitoring aims at increasing operational efficiency by understanding the periods in which the equipment is not operating. In this sense, the modelling of the harvesting operation allows us to analyze the times at which harvesters are not being used for the effective cutting of sugarcane, as shown in Figure 10.

The outside of the chart shows the grouping of productive hours, times in logistics, maintenance, and operational supplies. For the analyzed case, we verified 9.07 $h^{day\ -1}$ (37.8%) productive hours, in which sugarcane is actually being harvested.

The Pareto diagram – Figure 11, – allow us to identify the main offenders for the harvest performance.

Based on the scenario presented in Figure 11, we may state that:

Field maintenance and garage maintenance account for 24.1% of the Pareto diagram. To verify opportunities for improving the maintenance process, the times must initially be compared with market indicators – benchmark;

End-of-row maneuvering corresponds to 22.3% of the times when the harvester is not operating. The training of operators to operation synchronization may reduce the time to perform each maneuver, improving harvest. As state by Bernardes and Belardo (2015), where mechanized harvesting follows the rows and their paths, machines efficiency and productivity are proportional to the length and quantity of sugarcane per linear meter of the rows. Thus, another approach is to reduce the number of maneuvers through the proper planning of the physical

Figure 7 - Variations in Nominal Yield (NY) and Field Productivity (TCH) and its impacts on the loading–harvester ratio (Ralh) and loading operational yield (LOY) in 0.90 m x 1.40 spacing

Figure 8 - Variations in Nominal Yield (NY) and Field Productivity (TCH) and its impacts on the loading–harvester ratio (Ralh) and loading operational yield (LOY) in dual-row simultaneous harvest in 1.50 m spacing

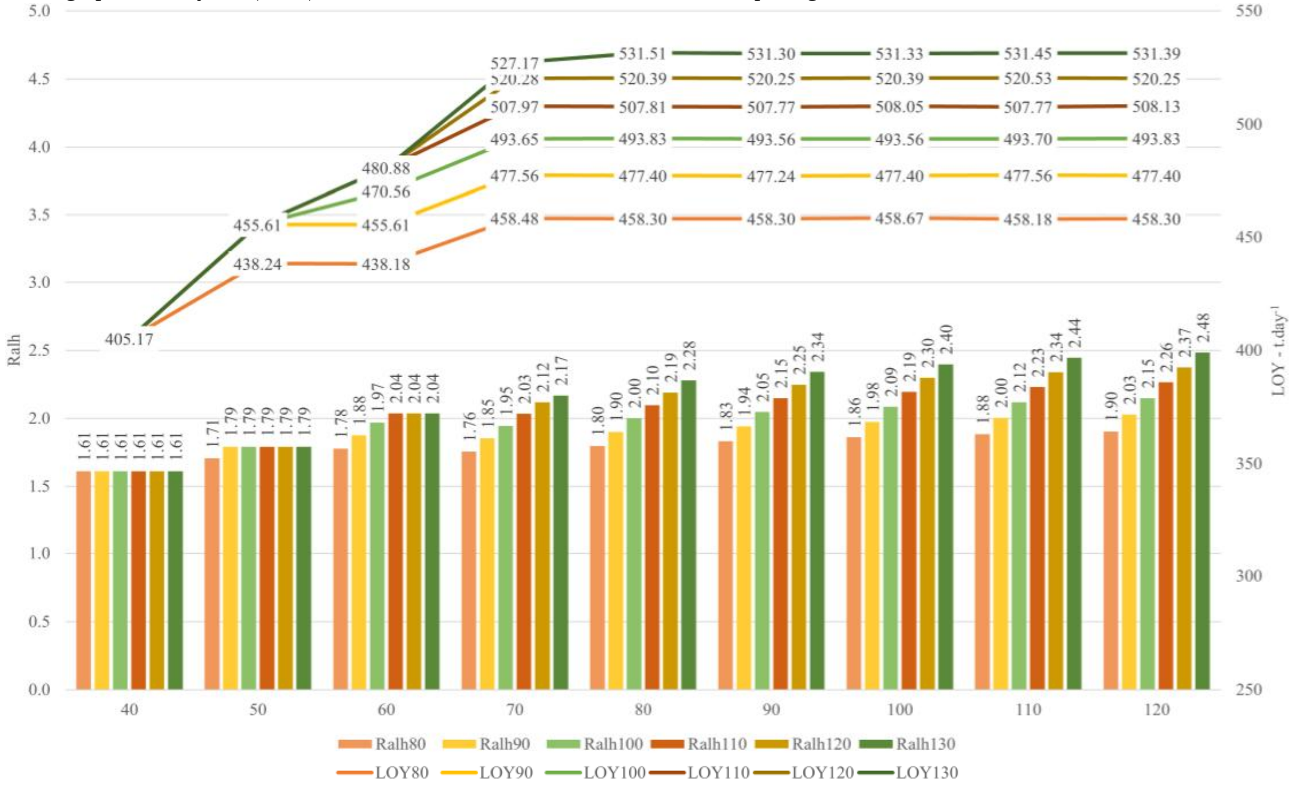
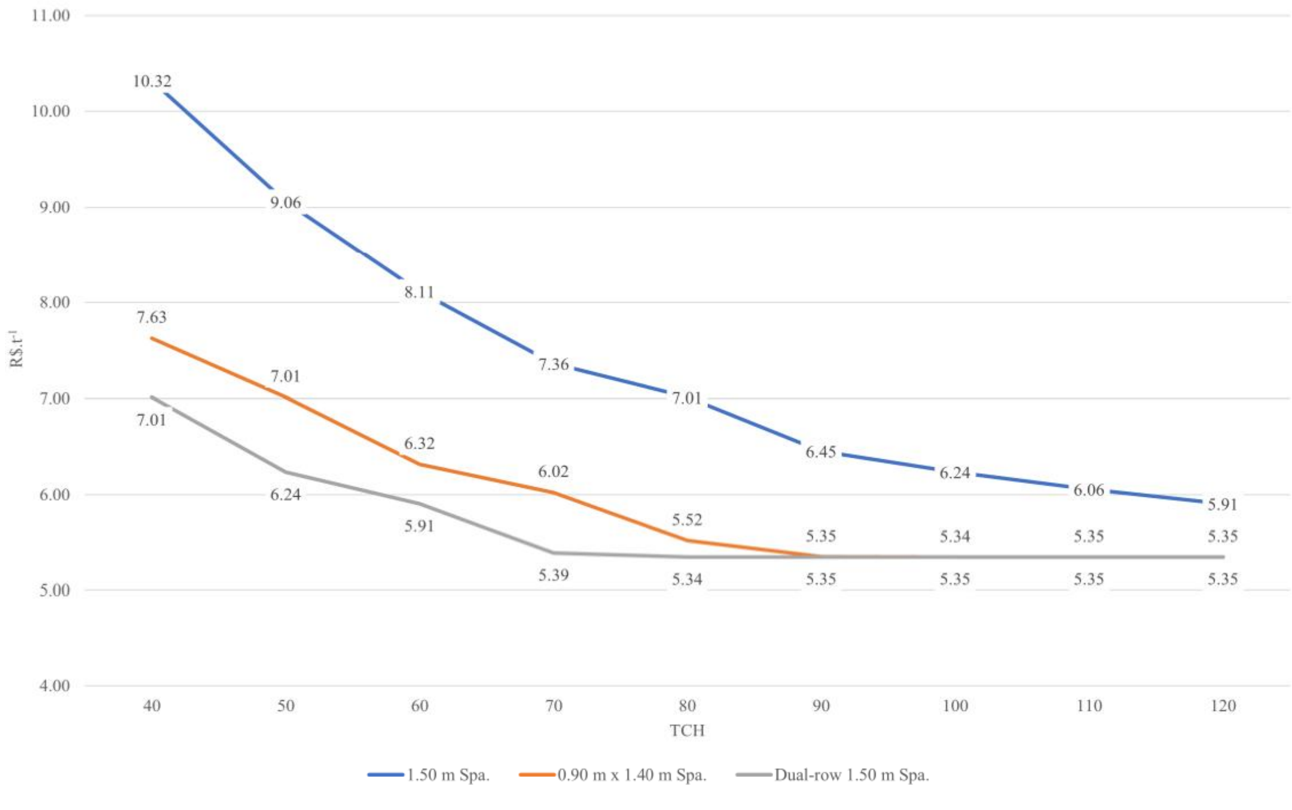


Figure 9 - Comparison of cost related to sugarcane loading in 1.50 m spacing, 0.90 m x 1.40 m spacing, dual-row simultaneous harvest in 1.50 m spacing



base. In maintaining the end-of-row maneuver (MT) at 110 seconds and changing trace length (TL), we obtain Figure 12, illustrating performance gains and reduction in harvesting costs; this indicates that the stages of soil conservation, physical planning, soil preparation, and mechanized harvesting must be integrated.

Nonproductive hours, associated with poor management and planning failures, account for 12.3%. Managing real-time information obtained by onboard computers is an important ally in reducing nonproductive hours. The integrated model of cutting and loading operations allows the sizing of loading equipment according to harvestability index (HI) and TCH – Figure 13. As the loading/harvester ratio is fractionated, the number of harvesters must be upsized and the number of loadings must be upsized to a whole number based on Ralh;

Meal stops, which correspond to 10% of offenders according to the Pareto diagram, are linked to labor laws, so that few actions can be taken in this sense. Thus, employers should examine the legislation for the possibility of converting part of these hours into work overtime;

The time used for equipment cleaning represents 6.7% in the Pareto diagram. This activity aims to reduce fire hazards and assist in the identification of possible leaks and structural damage, enabling preventive corrections;

Auxiliary maneuvers, which account for 4.9%, are related to the need for the harvester to swerve to avoid trees, erosions, and other obstacles present in the field. Whereas tree removal is associated with environmental legislation, erosions will be controlled during field reform – although their prevention necessarily goes through the stages of physical planning.

The mechanized harvesting system is an important cost component in the sugarcane agroindustry, corresponding to about 40% of the cost related to raw materials (DIAS NETO, 2015), thus justifying the detailed analysis of costs composition.

The integration of agricultural processes, from adequate physical planning to localized preparation and mechanized harvesting system with assisted steering devices, enables TCS implementation. This environment favors the adoption of simultaneous

Figure 10 - Percentage distribution of mechanized harvesting operation in 1.50 m spacing in 24 hours

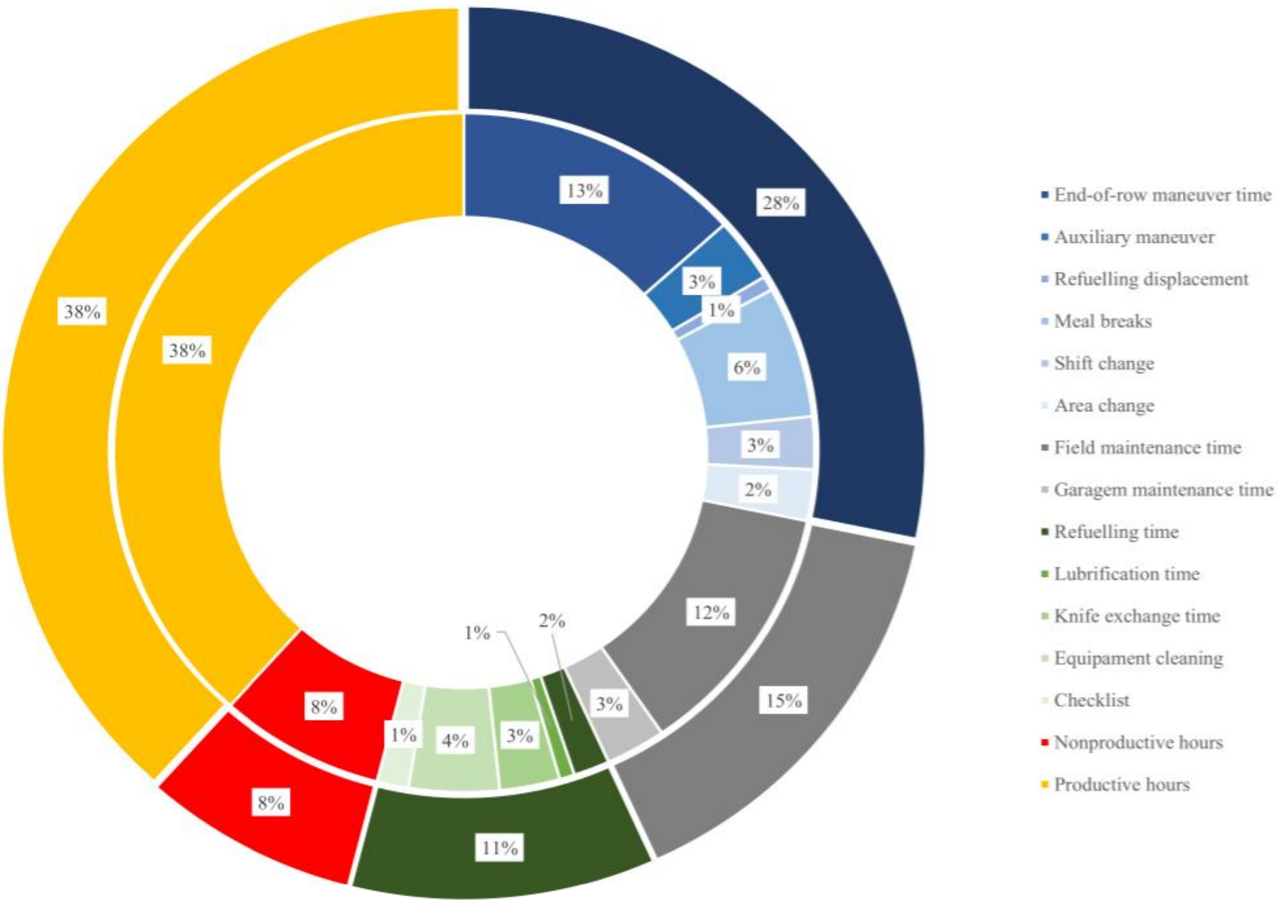


Figure 11 - Pareto diagram for offenders of mechanized harvest

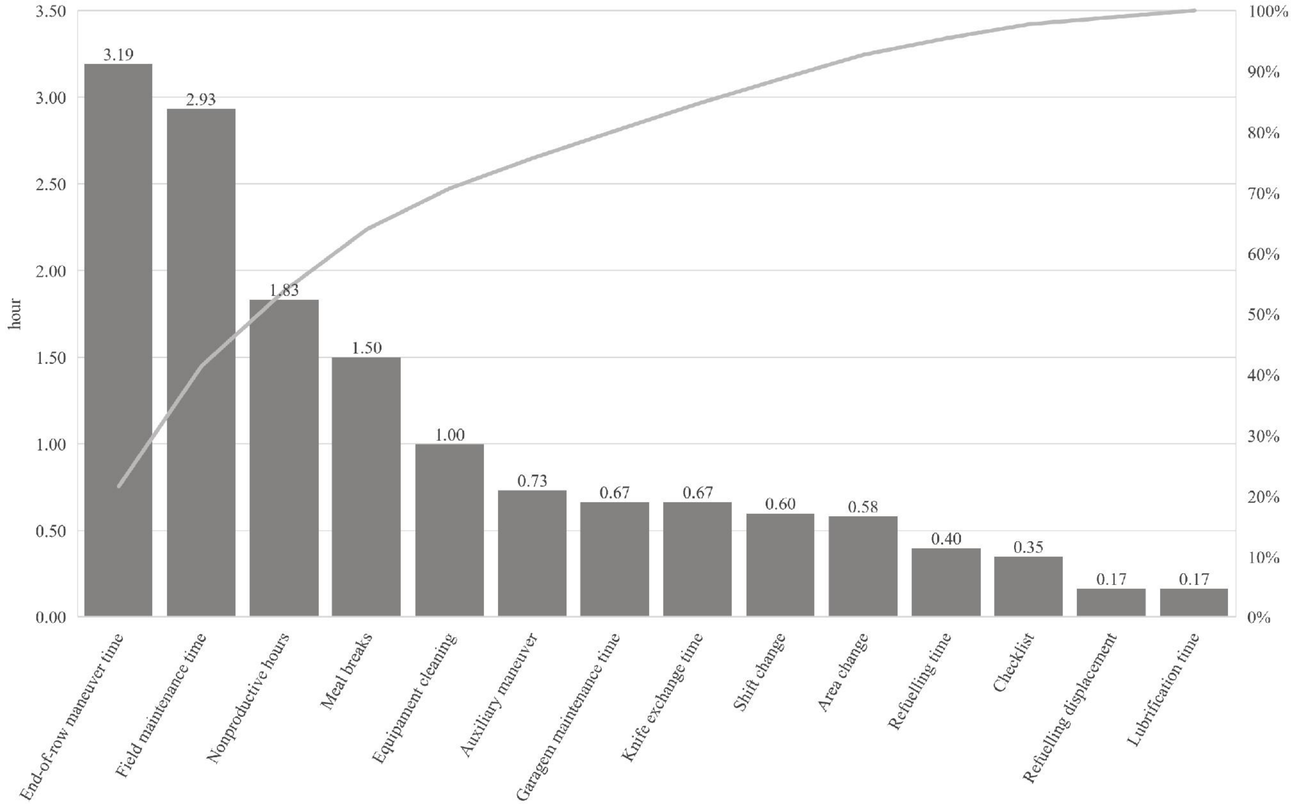
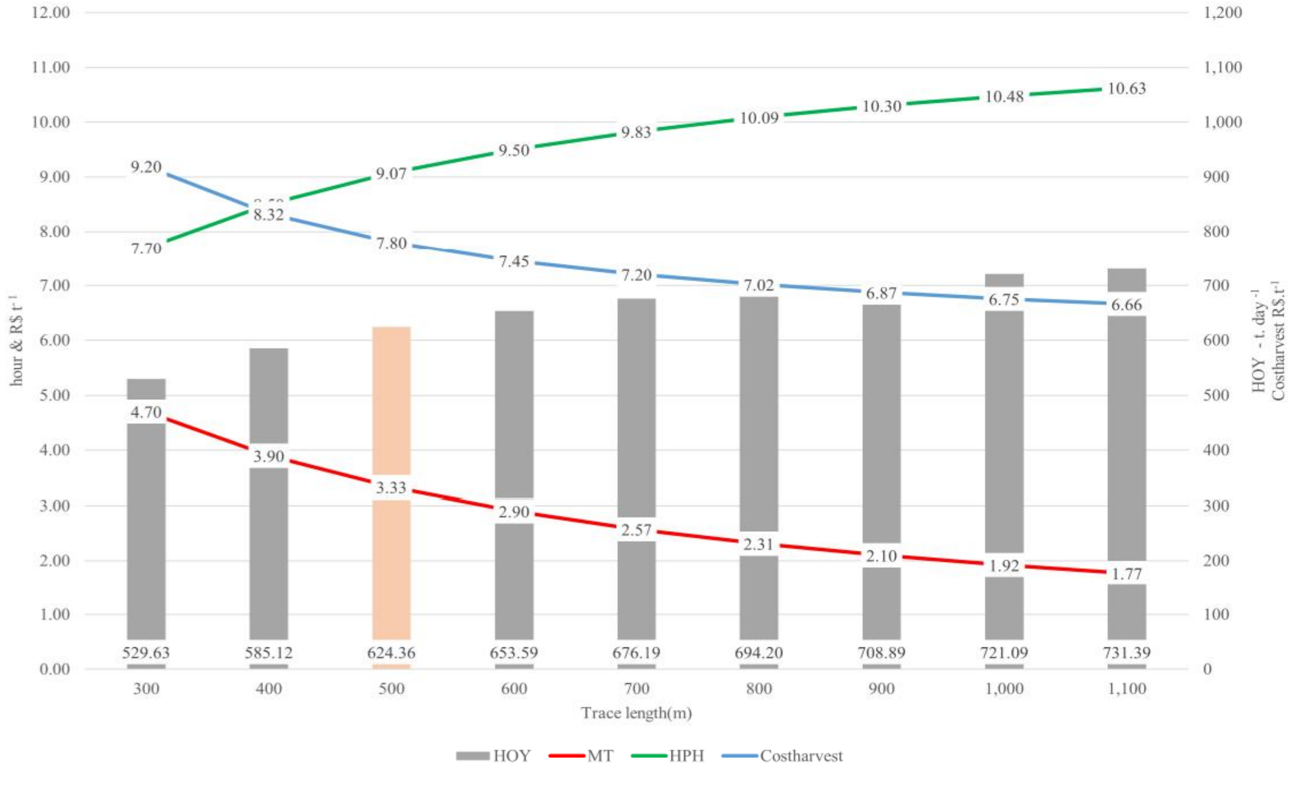


Figure 12 - Impact of the trace length on the operational performance of sugarcane harvester in 1.50 m spacing. HOY: harvester operational yield; MT: end-of-row maneuver; HPH: harvester productive hours; and Costharvest: cost of mechanized harvesting R$.t[-1]



mechanized harvesting in more than one row without causing damage to the ratoon by machines trampling, especially in 1.50 m spacing. The analysis of cost composition for the scenario presented in Table 10 and for the cutting and loading operations presented in Figure 14 shows diesel reduction between 0.39 and 0.50 l t^{-1}. This suggests that, besides reducing costs, this method also has a positive impact in reducing greenhouse gas emission (GGE).

Figure 13 - Loading sizing according to TCH, harvester operational yield (HOY), and loading operational yield (LOY) for 1.50 m spacing

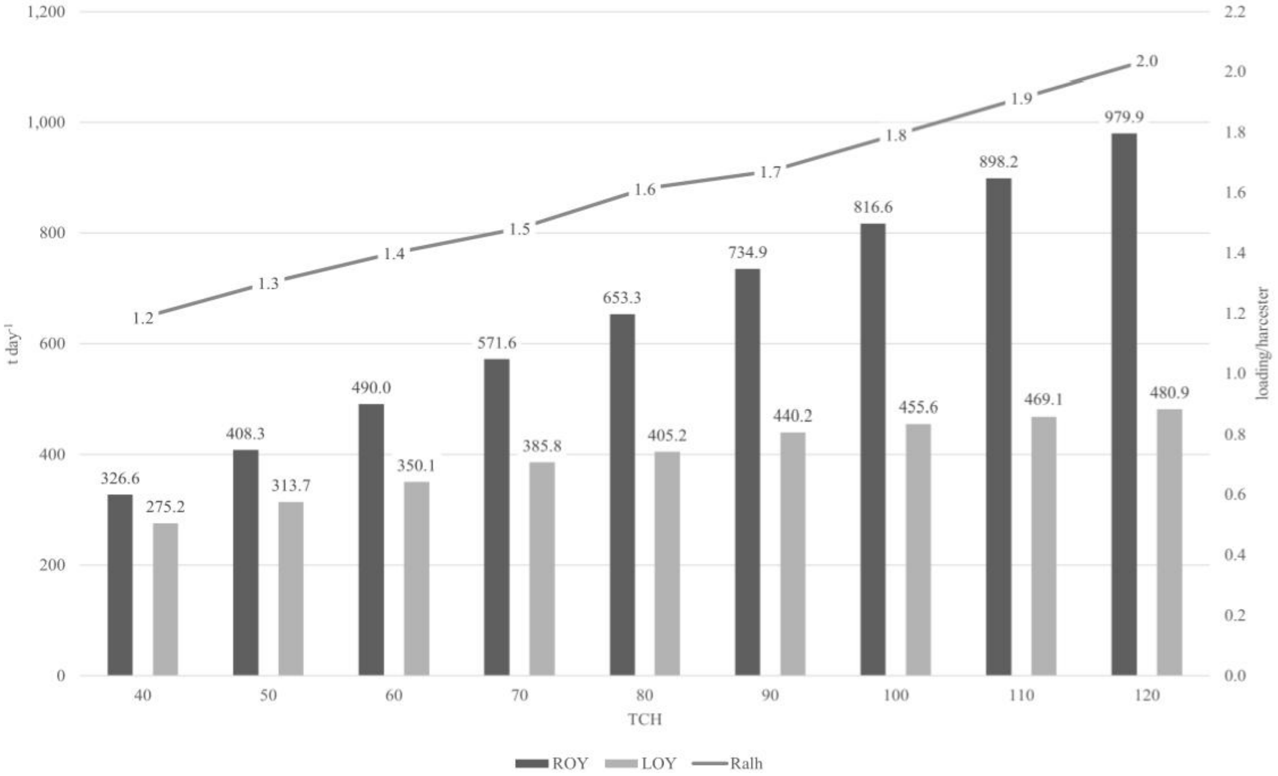
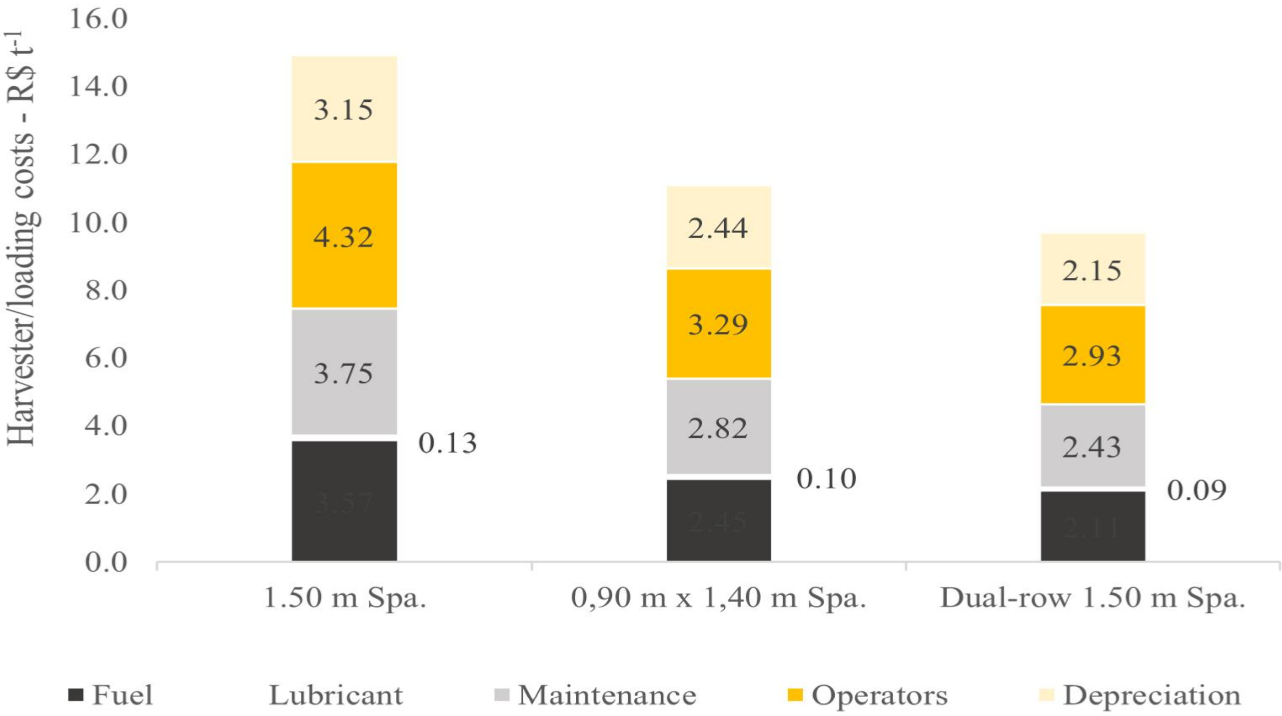


Figure 14 - Cost sharing of sugarcane cutting and loading operations according to spacing



CONCLUSIONS

The modeling and sensitivity analysis allow the evaluation of agricultural operations that are relevant in cost composition. Simulations showed that sugarcane harvesting operation is affected by the field productivity, which has a direct impact on the harvester operational condition. Moreover, the costs tend to stabilize as field productivity approaches the nominal yield adopted in the analysis. The model allows the dimensioning of a harvest front according to its agronomic conditions, as well as the operational conditions of times and movements obtained by agricultural automation. The results obtained in this study may be explored for solving operational bottlenecks, seeking to improve the harvester performance. It is important to note that this model was validated in a field trial before the begin the analysis using Chi-square test at a significance level of 0.05.

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