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Research Paper

Cost of boundary manoeuvres in sugarcane production

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Machinery has direct and indirect costs associated with their work in field, with non-productive time spent in manoeuvres when machinery reaches field borders. Much work has been carried reducing the number of manoeuvres in complex field shapes and changing the type of manoeuvre in order to speed them up. Biofuel producing crops such as sugarcane (*Saccharum* spp.) besides requiring economic profitability demand positive energy output in their production chain. Sugarcane uses narrow width equipment which requires time-costly manoeuvres adding significant inputs particularly on short rows. Using a method and calculations that is applicable for other crops, this study takes operational, spatial, economic, and energy factors into account to observe the impact of manoeuvres at the headland of a sugarcane crop. Energy and economic costs were retrieved from the hourly use of machines for four main field operations and their respective manoeuvring costs. Crop parameters were retrieved with their data compared with operational costs to establish the dimensions of row-length benefits. Increases in row length and width has decreasing benefits that may conflict with the logistics of servicing auxiliary units. The impacts of turning patterns were obtained, it suggests changes to minimise time and space for manoeuvring in planting and cultivating operations, and using wider roads and more steerable carriers in harvesting operations. In standard scenarios of a production system it was found that the income from row lengths less than 50 m were less than the economic costs occurred in turning at the headland.

1. Introduction

There are environmental and economic costs associated with the operation of machinery in agricultural fields. Soil compaction, overlap of worked area and the acquisition and operation of the suitable machinery are among the factors that can negatively impact on the sustainability of the agricultural production. Generally, agricultural machines do not spend much time in a field fully carrying out the operation

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Nomenclature

ARL	average row length being cover by the operation (m)
CRME	cost of manoeuvring in a row-edge (MJ or US$)
DBA	distance between implement and front tractor axles (m)
DBT	distance between turns within a U-turn (m)
D-MDS	distance followed by the tractor parallel to the road to the manoeuvre dedicated space (m)
EFB_{area}	energy or financial balance per area (MJ ha^{-1} or US$ ha^{-1})
$EFB_{metre\text{-}row}$	energy or financial balance per metre-row (MJ m^{-1} or US$ m^{-1})
Eh	hourly energy input (MJ h^{-1})
EMCRL	equivalent manoeuvre cost in row length (m)
Emw	energy given per unit weight (N kg^{-1})
F	yearly frequency of occurrence of the operation
fv, *rv*	forward and rearward velocities (m s^{-1})
h	length of the overlapping zone (m)
ICMA	input cost of manoeuvring per area (MJ ha^{-1} or US$ ha^{-1})
LT	hourly lifetime of the implement (h)
M	mass of implement (kg)
MDS	manoeuvre dedicated space, a wider width of the roads required for the P-turns.
NRC_{Oper}	number of rows covered by the operation
Oper	identifier of the field operation
Pm	average power output of the tractor during its lifetime (kW)
Pn	nominal power of the tractor (kW)
P-turn	manoeuvre type executed by an agricultural machine operating in a headland pattern. The machine moves into a region which allows a full loop turn
q	angle between machine direction and a perpendicular field border (in radians)
qme	manufacturing and repair and maintenance energy per unit fuel consumption (MJ g^{-1})
qs	specific mean consumption (g kW^{-1} h^{-1})
r	turning radius (m)
RRM	ratio of repair and maintenance energy to manufacturing energy
RTM_{Oper}	relative time spent in manoeuvering (%)
TCMRE	sum of manoeuvring operations costs in a headland (MJ or US$)
TC_{Oper}	time cost of a manoeuvre (MJ h^{-1} or US$ h^{-1})
Ti	hourly lifetime of the tractor (h)
TM_{Oper}	time spent in a manoeuvre for the operation (s)
T-turn	manoeuvre type executed by an agricultural machine operating in a headland pattern. Also known as reverse turn, the machine turns to one side and then reverses to be able to reach an adjacent machine track
U-turn	Manoeuvre type executed by an agricultural machine operating in a headland pattern. The steering does not exceed 180° for turning to reach a next machine track
w	width of the operation (m)
WMS, *UMS*, *TMS* and *PMS*	respectively the W-turn, U-turn, T-turn and P-turn manoeuvring spaces required (equivalent to the road or headland width, in m)
WMT, *UMT*, *TMT* and *PMT*	respectively W-turn, U-turn, T-turn and P-turn manoeuvring time cost (s)
WPR	weight per power ratio (N kW^{-1})
WS	working speed of the operation (m s^{-1})
Ω-turn	manoeuvre type executed by an agricultural machine operating in a headland pattern. The steering exceeds 180° for turning in the shape of a lamp-bulb to reach a following machine track

they were designed to perform. Loading or offloading agricultural products and inputs and turning are the main non-working factors that contribute to overall efficiency (Witney, 1996); reducing these non-productive periods reduces production costs.

An increasing proportion of sugarcane production is shifting towards fully mechanised field operations. However, the high biomass harvested and the narrow width of machines makes highly demands per area leading mechanisation and increasing the initial cost of production (mechanisation is 40% of the cost, Milan, 2004).

In Brazil, ethanol for automotive fuel is derived from sugarcane and is used either pure or blended with gasoline (18–25% of ethanol). This ethanol is basically produced in sugarcane mills and distilleries, and the crop covers close to 9 million ha in the country (CONAB, 2013).

The energy balance for the sugarcane crop has been studied. As a bioenergy supplier it is expected that the energy produced by the crop to safely excel its inputs. Macedo, Seabra, and Silva (2008) found ratios of the output/input of sugarcane energy of 9.2 considering an input of 15.2 GJ ha^{-1}, while De Oliveira, Vaughan, and Rykiel (2005) obtained a ratio of 3.7 and an input of 36 GJ ha^{-1}. These studies were carried using a holistic approach focussing in the hectare as the research unit. Macedo et al (2008) calculated the embodied energy (per Mg) of sugarcane, from field production to the stage of energy products (ethanol and electricity). This latter approach gives a more accurate estimate, once the logistic costs of the production and processing are more specifically related to product quantity rather than area.

Coelho (2009) pointed that mechanisation of harvest operations in sugarcane can amount from 30 to 35% of production costs. Efficiency issues found that a sugarcane harvester spends only an average of 8.5 h of effective work in a continuous 24 h of work (three shifts each of 8 h).

Sugarcane is a row-crop where undesired machine traffic (i.e. across or in the rows) leads to damage of the ratoon which requires the crop has to re-establish and grow again. Around

5–6 crops can be taken from the same ratoon before replanting is required making the crop very attractive for controlled traffic farming (Paula & Molin, 2013). To control traffic, machine tracks are a multiple of the row width, and cropped headlands parallel to roads/borders are absent in order to avoid being overrun by machines.

Because of the high output of harvested per area, an intensive transport system of primary and secondary roads occupying from 2 to 4% of the total area, with widths of 8 and 5 m respectively, is required (Benedini & Conde, 2008). These roads are also used for turning the field machinery and limits on their width impact on manoeuvring. Studies are required to find the optimal width for these roads considering such aspects.

In order to reduce the considerable impact of sugarcane mechanisation costs, recent efforts have been directed towards redesigning field features by relocating roads and erosion-control-terraces in order to establish planned crop rows (Guimarães, 2004).

Simulating machine paths to cover a field in advance, also known as path planning, to minimise the number of turns (Jin & Tang, 2006; Oksanen & Visala, 2009; Taïx, Souères, Frayssinet, & Cordesses, 2006) and the time for each turn (Bochtis & Vougioukas, 2008; Spekken & de Bruin, 2013) has been carried out. Although such approaches are capable of increasing field efficiency, the machine working pattern is always parallel which contrasts with many fields that do not have parallel borders and have obstacles. This results in short rows on field corners where turning-costs may surpass the benefits (economic or energy). Despite methods for detecting such tracks already been proposed within path planning (Spekken & Molin, 2012), the economic and energy criteria that define the costs of a turning edge of a row have not yet been determined, including the related row-length cost/benefit.

Considering energy and economic criteria, the following research questions are posed:

- What is the cost of manoeuvres in sugarcane in both time and inputs?
- What are the benefits for changing turning patterns on the edge of rows?
- What is the break-even length of a row with respect to manoeuvre cost?
- What is an optimal relationship between turning time and width of the roads?

2. Methodology

The methods for obtaining and analysing the data is described in four main sub-sections: overview of sugarcane machine operations; modelling the manoeuvres; the time and spatial cost of manoeuvring and its balance; and scenarios for calculating the impact of the manoeuvre-types.

2.1. *Overview of types of manoeuvre and sugarcane machine operations*

In general, in agricultural field operations, there are three main types of machine manoeuvres (Fig. 1): Ω-turns, U-turns and T-turns (Bochtis & Vougioukas, 2008). The angle between the working direction and the field border also influences manoeuvre behaviour and the space required for it (Jin & Tang, 2010; Spekken & de Bruin, 2013).

Ω-turns are the faster types of manoeuvres where machinery returns into an adjacent row, but it demands more manoeuvring space (Cariou, Lenain, Thuilot, Humbert, & Berducat, 2010), which demands wider headlands for manoeuvres and more area taken out of production. U-turns are fast and require less space for manoeuvring; they are feasible when the implement width is larger than diameter of the turning circle or when rows are skipped (Bochtis & Vougioukas, 2008) as shown in Fig. 1.

T-turns more commonly seen in sugarcane operations due to their low demand for manoeuvring space to reach an adjacent track. Shifting from T-turns to skipping rows is possible with the use of guidance systems, which assures parallelism and a correct skipping distance from the previous row.

In this work four main field operations are considered for determining sugarcane manoeuvring costs: planting, cultivating, spraying, and harvesting. These can be seen respectively in Fig. 2a–d.

Figure 2a shows a mechanised planting operation, which occurs usually every five years. It shows a standard sugarcane planter pulled by the tractor producing a 14 m long assembly which limits considerably its turning capacity. In Fig. 2b, a cultivator is attached to a tractor performing three simultaneous operations: cultivating, applying fertiliser and chisel-ploughing the soil; its manoeuvres are limited by the tractor steering capacity. Both planting and cultivating operations are limited to only two crop rows thus the working width is smaller than the diameter of turning. The spraying operation (Fig. 2c) is comparable to regular crops; its application width easily surpasses its turning capacity. Figure 2d shows sugarcane harvesting, in which two wagon-carriers pulled in line by a tractor receive the billets while moving alongside the harvester (similar to forage harvesting). The harvester generally covers a single row, nevertheless, recent machinery developments have increased harvesting widths up to 2 rows.

Because of the large turning radius of the carrier, the absence of crop-covered headlands and the limited width of roads, the wagons are main consumers of time in manoeuvres. Baio (2012) remarked that the sugarcane harvester is

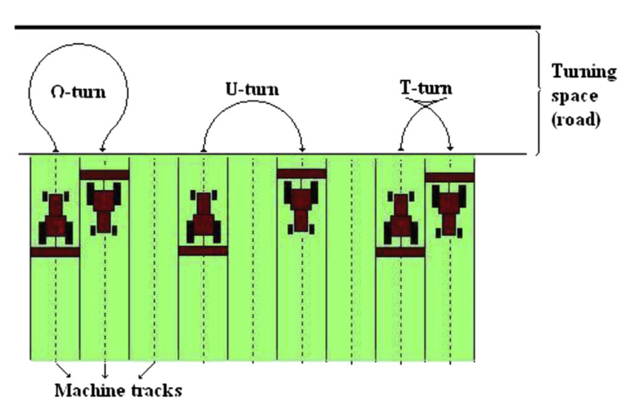

Fig. 1 – Types common manoeuvres in field operations (after Spekken & de Bruin, 2013).

Fig. 2 – Views of four operations carried out in sugarcane production: planting (a); cultivating (b); spraying (c); and harvesting (d).

capable of performing U-turns at the ends of the rows faster than the cane wagon and that the latter impairs the total operational field efficiency of the mechanised system.

Spraying operations regularly use of U-turns and their manoeuvre time is herein set to 20 s with its manoeuvring space fitted within the minimum existing road width.

Skipping rows is unsuitable during harvest since the machines cannot skip a row without overrunning and damaging a crop-row alongside. In many cases, a more elaborate manoeuvre is carried out where the machine travels a certain distance in order to reach a manoeuvre-dedicated-space (*MDS*) to turn and returns parallel to the harvester. This manoeuvre is herein designated as P-turn, due to the "P" shape of the turn (Fig. 3).

The tractor-double-wagon set (shown in Figs. 2d and 3) has a 10.8-m turning radius. A single-wagon set with equal storage capacity (larger basket) has a turning radius of 7 m. Self-propelled carriers (trucks with baskets) have a turning radius of 5 m.

2.2. *Modelling the manoeuvres*

For sugarcane fields, both the space required for turning and the time spend in a turn determines the cost of the manoeuvre. Regarding loop turns (i.e. Ω-turn and U-turn), a modified approach after Jin and Tang (2010) was used to obtain the space (headland or road) and time demanded for manoeuvring.

Both T-turns and P-turns are time demanding, and the time spent in these is dependent on operator skill, the distance to the *MDS* (if it is the case) and the type of wagon-carrier used (double-wagon carriers hardly use T-turns). Coelho (2009) suggested the time spent in harvesting manoeuvres for sugarcane to be of 50 s for a specific case study area, whilst Benedini and Conde (2008) consider the same manoeuvres to be of 1.5–2.0 min.

In the modelling a T-turn followed a modified U-turn which includes a rearwards motion, and one new approach was proposed to estimate the time spend in a P-turn. The three main variables that are required in the geometry of all the manoeuvres are the width of the operation (w), the turning radius (r) and the angle in which the machine heads towards a perpendicular field border (θ). Figure 4 shows the elaboration and influence of variables in the types of manoeuvres studied.

The angle θ can vary along the fields, but in sugarcane roads are often designed almost at right angles to the crop rows, the exception being with field corners. A general

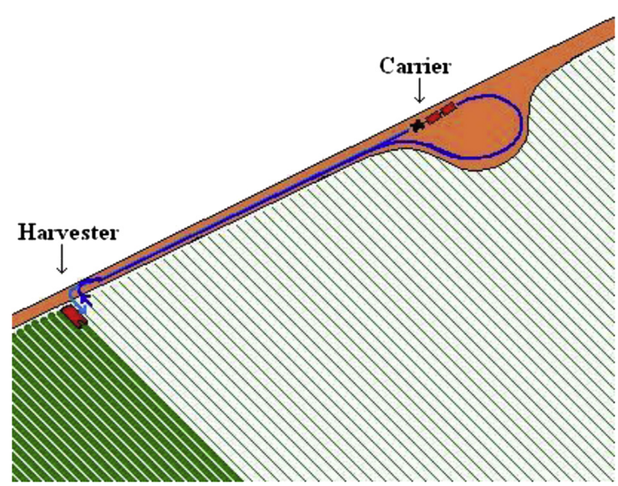

Fig. 3 – Long manoeuvre of a double-wagon carrier to avoiding overrunning the crop area.

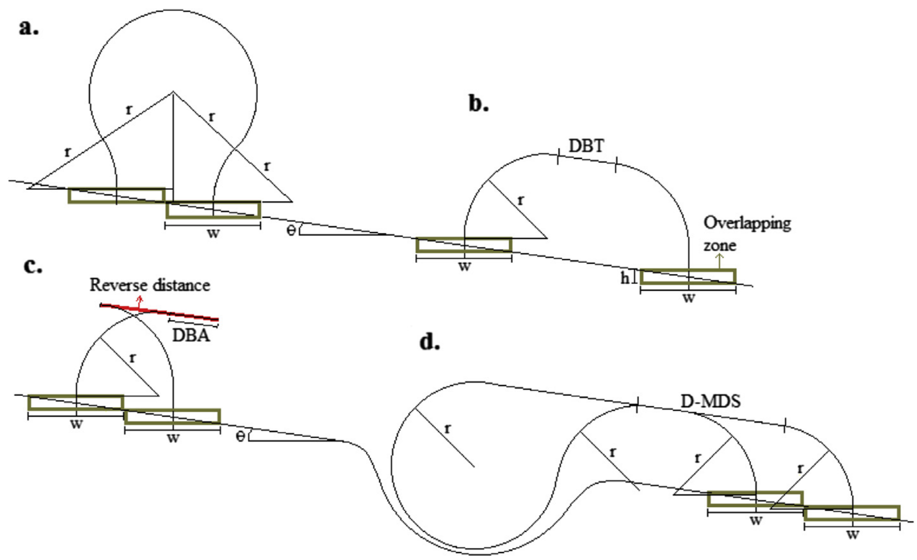

Fig. 4 – Composition of the types of manoeuvres: Ω-turn (a), U-turn (b), T-turn (c) and P-turn (d).

assumption is therefore made for θ to be 10° as a general standard value for calculations. In Fig. 4, h is the length of the overlapping zone, given by:

$$h = \frac{w}{\tan(90 - \theta)} \tag{1}$$

Sugarcane fields do not contain headlands, therefore there is no real overlap of pesticides and/or fertilisers. Because of the small width of most operations, the value of h is usually low. Its influence on the space required for manoeuvres is found with higher values of θ.

The variable *DBT* is the distance between steering within a U-turn, and is the difference between the length of skipped rows and the turning diameter. *DBA* is distance between implement and front tractor axles (single axle trailed implement) and is the minimum distance needed for a machine to become fully perpendicular to a field boundary before starting to follow a reverse track.

D-MDS is the distance followed by the tractor parallel to the road to reach the manoeuvre dedicated space before/after leaving the field.

2.2.1. *Space demand for manoeuvres*

The space demand for manoeuvres is related to the width of the road required for completing the manoeuvre. Exception is made for the P-turn because of its requirement for an *MDS*.

The minimum manoeuvring space required for the Ω-turn, U-turn and T-turn (*ΩMS*, *UMS* and *TMS*) are respectively given by Eqs. (2) and (3):

$$\Omega MS = r + \cos(\theta) * \left\{ \sin\left[\arccos\left(\frac{r + w/2 + \tan(\theta) * h}{2r}\right)\right] * 2r + \tan^2(\theta) * h \right\} + \frac{w}{2} \tag{2}$$

$$UMS = TMS = (\sin(\theta) + 1) * r + w/2 \tag{3}$$

The manoeuvring space for a T-turn was therefore taken as geometrically equal as the space for a U-turn.

For the P-turn the space demand considers a space for manoeuvring and travelling along the road (road width) and the space of occupied by the *MDS* (*MDS width*), both of which can be seen in Fig. 5 and used in the full space demand calculation.

In Fig. 5, the node $n1$ is located at minimum distance necessary, in length, for a machine to perform a P-turn (considering the location from the start of the steering in $n1$ to the centre of the *MDS*), which is given by:

$$\textit{Minimum distance to MDS} = 2r + \cos(\theta) * r \tag{4}$$

The road width is obtained by:

$$\textit{Road width} = r - r * \sin(\theta) + w/2 \tag{5}$$

The *MDS* width is obtained by:

$$\textit{MDS width} = 2r + w - \textit{Road width} \tag{6}$$

Considering the node $n2$ as the farthest point from which a machine would go for a specific *MDS*, a longer distance would lead the machine using another *MDS* near to the field. The equivalent full width (manoeuvring space required for a P-turn: *PMS*), can be given by:

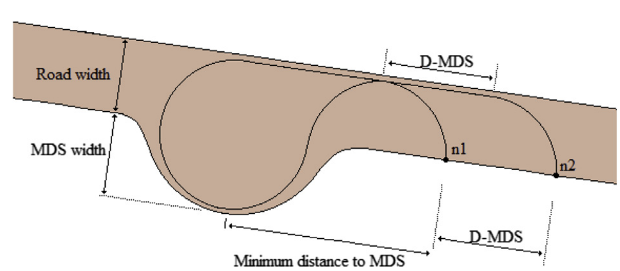

Fig. 5 – Space requirements for a P-turn.

$$PMS = Road\ width + \frac{\left[\pi^*(MD\ Swidth)^2/2\right]}{MDS\ width + Mininum\ Distance\ to\ MDS + D - MDS} \quad (7)$$

2.2.2. *Time demand for manoeuvres*

The time for manoeuvring is obtained by the ratio of length of the manoeuvres (modelled after their elaboration in Fig. 4) and the velocity of the machine along this manoeuvring pattern. Agricultural machinery generally uses a constant engine throttle, therefore the manoeuvring velocity is likely to remain the same for a selected manoeuvre in a specific gear. Fluctuations in speed may occur between gear shifts during (or before) entering/finishing the manoeuvre, but the value is here considered less significant.

The times spend for Ω-turn and U-turn are respectively given by Eqs. (8) and (9):

$$\Omega MT = \frac{r}{fv}^*\left\{2^*\left[\arccos\left(\frac{r + w/2 + \tan(\theta)^*h}{2r}\right) + \arccos\left(\frac{r + w/2 - \tan(\theta)^*h}{2r}\right)\right] + \pi\right\} \quad (8)$$

$$UMT = \frac{(\pi r + DBT + 2r^*\tan(\theta))}{fv} \quad (9)$$

where ΩMT, UMT are corresponding lengths followed by a machine in each manoeuvre. While for the loop turns the machine motion is at constant forward velocity, for the T-turn the time spent is a sum of: a forward steering time (before and after reversing), given by the ratio of forward distance by the forward velocity); a straight reversing time, given by the ratio of the reverse distance by rearward velocity; and two stopping times required to cease the machine movement and change the gears between reversing direction. As the stopping movement is not instantaneous for any moving machine, a simplification is considered in this work adding the deceleration time to the stopping time in the reversing direction steps. To obtain the T-turn time (TMT), a composite of two distances are separated in forward and rearward motions are summed in Eqs. (10), (11) and (12).

$$TMT = \frac{Forward\_distance}{fv} + \frac{Reverse\_distance}{rv} + 2^*(Stop\_time) \quad (10)$$

$$Forward\_distance = \pi r + 2r^*\tan(\theta) + DBA \quad (11)$$

$$Reverse\_distance = DBA + 2(r - w) \quad (12)$$

In the P-turn therefore, the time calculation is also split into two distinct velocities in Eqs. (13), because it is considered that it contains a steering motion followed at a regular velocity (fv_1) and a significant longer straight motion driven in faster velocity (fv_2). Therefore, in this work, the manoeuvre time is split into two different lengths determined by two different velocities:

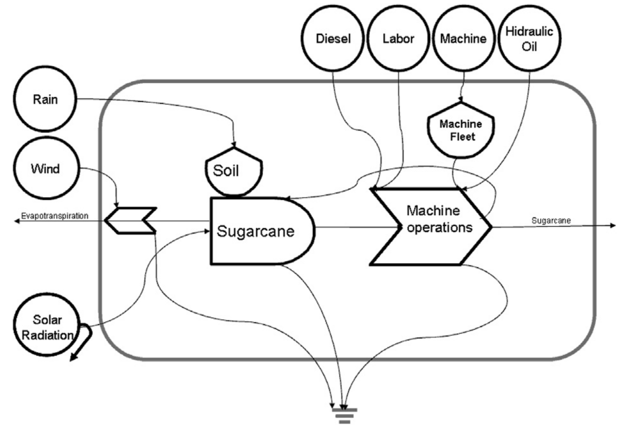

Fig. 6 – Diagram of material flow in a mechanised sugarcane production system. Modified after Romanelli and Milan (2010).

$$PMT = \frac{2r\left(3\pi/2 - \theta\right)}{fv_1} + \frac{2(r + D - MDS) - w}{fv_2} \quad (13)$$

2.2.3. *The choice of manoeuvre type*

For some operations the choice of a manoeuvre could be just a matter of time spent when there are no issues in requirements for space. While for others, the choice for manoeuvre must consider a balance between the loss of area (demand for space) and time consumption.

Two costs are here considered for space and time consumption in manoeuvres: energy and economic.

2.3. *The time and spatial costs of manoeuvring and their balance*

2.3.1. *Manoeuvring cost in time proportion*

For any operation in a field, the fraction of time spent in a manoeuvre considering the working time within the length of a row is given by the working speed of the machine and the time of the manoeuvre in Eqs. (14). The relative time spent in manoeuvring is given by:

$$RTM_{Oper} = \frac{TM_{Oper}}{\left(ARL/WS\right) + TM_{Oper}} \quad (14)$$

where RTM_{Oper} is the relative time spent in manoeuvring (%); TM_{Oper} is the time spent in a manoeuvre for the operation (s); WS is the working speed of the operation (m s^{-1}) and ARL is the average row length for the operation (m). The variable RTM_{Oper} is the fraction of time spent by a machine in the manoeuvring operation, which is not dependent on the width of field coverage.

2.3.2. *Calculating manoeuvre input costs*

The inputs embodied in sugarcane, or the input materials required for its production are shown in Fig. 6, with a diagram of the material flow. In Fig. 6, the inputs regarding machine

Table 1 – Parameters and calculated hourly energy cost of the implements used in the sugarcane operations.

Equipment	Mass (kg)[a]	Lifetime (h)[a]	Ratio of the lifetime R&M energy to manufacturing energy[c]	Energy for manufacturing + R&M, (MJ h^{-1})
Sugarcane planter	6300	10,000	0.55	87.89
Cultivator	1100	10,000	0.55	15.35
Sprayer	1000	4000	0.37	30.83
Sugarcane transporter[b]	10,900	21,000	0.3	60.73

[a] The mass, lifetime and width are typical for the type and size of the machine in Brazilian market in 2013.
[b] Lifetime, width and velocity in same pace as the sugarcane harvester.
[c] Coefficients presented by Bowers (1992).

operations are given by diesel, labour, machine and hydraulic oil. In this study, these are the inputs considered in the operational costs, which are calculated by economic and energy variables.

The financial values found in literature were subject to currency conversion from Brazil Real dollar (R$) to United States dollar (US$). Considering the period for which the values were obtained, the exchange rate was of 1.77 R$ US$$^{-1}$ in January 2008 to 2.37 R$ US$$^{-1}$ in January 2014. The average of the monthly ratio for this period (72 months) was therefore 1.97 R$ US$$^{-1}$, which was the value used. The cost variable was finally obtained in units per time (MJ h^{-1} or US$ h^{-1}) for which all the operational decision-making costs are obtained.

2.3.3. *Hourly energy input*

The respective implements used in these operations are given in Table 1, A single class of power tractor was used for all the operations (Table 2). The operation of harvesting demands three machines: a tractor, a sugarcane carrier and a harvester.

To obtain the relation energy/time, the indirect and direct energy inputs required for a machine are calculated. Manufacture, and repair and maintenance (R&M) are the mechanisation indirect inputs here considered.

To calculate the indirect energy input of the machines the approach of Mikkola and Ahokas (2010) is used. Equation (15) shows how the calculation was carried out for self-propelled agricultural machines.

$$qme = \frac{Emw \cdot WPR \cdot Pn}{qs \cdot Ti \cdot Pm} \tag{15}$$

where: qme is the manufacturing and R&M energy per unit fuel consumption (MJ g^{-1}); Emw is energy given per unit weight (MJ N^{-1}); WPR is the weight per power ratio (N kW^{-1}); Pn is the nominal power of the tractor (kW); qs is the specific mean consumption (g kW^{-1} h^{-1}); Ti is the hourly lifetime of the tractor (h) and Pm is the average power output of the tractor during its lifetime use (kW).

The calculation for hourly energy input of implements is shown in Eq. (16) adapted after Mikkola and Ahokas (2010) to an hourly energy demand.

$$Eh = \frac{Emw \cdot (1 + RRM) \cdot M}{LT} \tag{16}$$

where: Eh is the hourly energy input (MJ h^{-1}); RRM is the ratio of R&M energy to manufacturing energy; M is the mass of the implement (kg) and LT is the hourly lifetime of the implement (h).

The manufacturing energy (Emw) was 90 MJ kg^{-1}. The specific parameters of the machines and the respective indirect energy consumption are given in Tables 1 and 2.

2.3.4. *Economic input and final hourly costs*

Studies of hourly economic inputs in sugarcane machine operations are more widely available. In full work efficiency, Zacharias, Santos, and de Jesus (2011), found a cost of 45.70 US$ h^{-1} for mechanised sugarcane planting. Baio and Moratelli (2011) observing the use of auto-guidance systems obtaining a cost of tractor-planter set of 76.43 US$ h^{-1} with a respective 75–25% cost distribution of the set and a field efficiency of 68%. For cultivating and spraying operational costs were extracted from AgraFNP (2012), which also provides the data for economic balance.

In harvesting operations, Salvi, Oliveira, Fioravente Filho, and Santos (2010) proposed a method that first set the field

Table 2 – Hourly energy cost and parameters for indirect and fuel energy input of the self-propelled equipment used in the sugarcane operations.

Equipment	Energy for manufacturing + R&M (MJ h^{-1})	Output power (kW)	Specific fuel consumption (g kW^{-1} h^{-1})	Hourly consumption (L h^{-1})[c]	Fuel energy input (MJ h^{-1})[d]
Sugarcane harvester	159.9[a]	180	260	57.07	2185.9
Tractor	41.51[b]	80	280	27.32	1046.24

[a] Mantoam, Milan, Gimenez, and Romanelli (2014).
[b] Considering power of 132 kW, mass of 9000 kg and lifetime of 16,000 h.
[c] Density for diesel fuel of 0.82 kg L^{-1}.
[d] Energy output of diesel of 38.3 MJ L^{-1}.

efficiency (in his study 65%) and the number of harvesters necessary to harvest a certain area, rounding up the non-integer demand for machines in the site. The authors calculated costs per Mg of sugarcane harvested obtaining a cost of 2.12, 1.92 and 1.70 US\$ Mg^{-1} for yields of 80, 90 and 100 Mg ha^{-1}, respectively. The final economic and energy costs used for calculating the cost balance of manoeuvres are shown in Table 3.

2.3.5. *Cost of a manoeuvre per crop row*

The yearly cost of manoeuvring in a row boundary was designated *CMRE* and is dependent neither on *WS* nor in the *ARL*, but on the time for manoeuvring, the time-cost of the operation, the frequency of operating along the plant row and the number of rows covered by the crop. Its calculation is given in Eqs. (17) and (18).

$$CMRE_{Oper} = TM_{Oper} \cdot \frac{TC_{Oper}}{3600} \cdot \frac{F}{NRC_{Oper}} \tag{17}$$

$$TCMRE = \sum_{Oper} (CMRE_{Oper}) \tag{18}$$

where: *CRME* is the cost of manoeuvring in a row boundary (MJ or US\$); *Oper* is the identifier of the field operation; TC_{Oper} is the time or cost of a manoeuvre (MJ h^{-1} or US\$ h^{-1}); *F* is the yearly frequency of occurrence of the operation; NRC_{Oper} number of rows covered by the operation and *TCMRE* is the sum of the costs of manoeuvring operations in a row boundary (MJ or US\$).

2.3.6. *Manoeuvring cost per area*

The cost per area is given by the number of manoeuvres in a unit area unit multiplied by the *TCMRE*. The area unit used was the hectare (ha).

The number of manoeuvres was obtained by dividing the area unit by an average of the area of one crop row. The calculation is shown in Eq. (19).

$$ICMA = \frac{10,000}{ARL * Row\ width} \cdot TCMRE \tag{19}$$

where *ICMA* is the input cost of manoeuvring per area (MJ ha^{-1} or US\$ ha^{-1}).

Table 3 – Energy and economic costs for the operations.

Operation	Energy input (MJ h^{-1})	Economic input[a] (US\$ h^{-1})
Planting	1175.64	80.46[b]
Cultivating	1103.10	36.53[c]
Spraying	1118.58	38.86[d]
Harvesting	3494.28	170.98[e]

[a] Operator hourly wage of US\$ 2.55 added to each operation for an 8 h daily shift labour (AgraFNP, 2012).
[b] Costs distributed in: 72.8% tractor (148.7 kW) and 24.13% sugarcane planter (Baio & Moratelli, 2011).
[c] 88.3 kW tractor with a two row triple operation implement: fertiliser distribution, subsoiling and cultivation (AgraFNP, 2012).
[d] 18 m boom sprayer pulled by a 66.2 kW tractor (AgraFNP, 2012).
[e] Salvi et al. (2010), considering a yield of 90 Mg ha^{-1} and a cost of harvest of 1.92 US\$ Mg^{-1}.

Despite *ARL* having a direct impact on production cost, no studies exist indicating an average value in sugarcane fields nor their quantitative impact in machine operations. Thus *ARL* was considered as a variable.

The width of the coverage of a machine also directly impacts on spatial turning costs. Figure 7 illustrates the types of sugarcane harvester coverage capacity. In general, sugarcane is harvested one row at a time (as in "i"), but machine developments allowed harvesters to enlarge their width to harvest narrow twin-rows ("ii") and more recently machines have been enlarged to harvest two sugarcane rows ("iii").

2.3.7. *Energy and economical balance*

Both the energy and financial output of sugarcane can be calculated using crop productivity. The energy balance was calculated following Macedo et al. (2008) who calculated the energy input and crude output of sugarcane to be of 233.8 MJ and 2185.2 MJ respectively. The estimated yields along the harvest sequences, the financial input and output were extracted from AgraFNP (2012).

Financial balances fluctuate through the years because of the price paid for Mg of cane. The production costs were considered fixed for a five-year set plantation, but they has distinct costs for each harvest-year. Each sequential harvest from the same base-ratoon gives decreasing yields until it reaches a critical economic point where it requires replanting.

A total of five harvests from one planting are common. The energy balance follows linearly while Table 4 displays the data used for the economic balance.

As the economic revenue may vary along the years because of factors such as sugarcane price, yield or distinct case-sites of production costs, and because of the small fraction of economic revenue compared to the whole cost; unique costs (such as manoeuvring) have significant influence in the final revenue. In order to study this influence, the net output shown in Table 4 was be subject to increase profitability in the order of 50%, 75% and 100% within the scenario studies.

2.3.8. *Impact of a manoeuvre within a row*

Each crop-row is considered here to have a fixed *TCMRE* and a specific net output (energy or economic). By adding cost of a manoeuvre per area (*ICMA*) to the final balance of sugarcane production, a net output is obtained free of manoeuvring costs. This value is adjusted to units of linear revenue of the

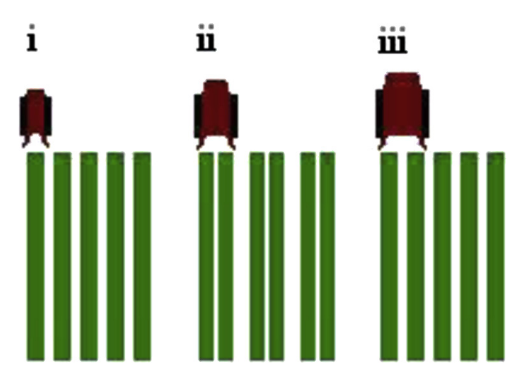

Fig. 7 – Distinct width configurations available for sugarcane harvesters.

Table 4 – Economic balance of the sugarcane production.

Harvest year	Yield (Mg ha^{-1})[a]	Cost (US\$ ha^{-1})[a]	Profit (US\$ ha^{-1})[a]
1	106	2822.27	832.64
2	84	2224.34	678.24
3	76	2333.67	273.57
4	66	2106.21	178.23
5	58	1952.84	35.75
Average	78	2287.87	399.68

[a] Yield, cost and profit extracted from AgraFNP (2012).

crop row. Eq. (20) shows the sugarcane balance to a row-metre.

$$EFB_{meter-row} = \frac{(EFB_{area} + ICMA) \cdot Row\ width}{10,000} \tag{20}$$

where: $EFB_{metre\text{-}row}$ is the energy or financial balance per metre-row (MJ m^{-1} or US\$ m^{-1}) and EFB_{area} is the energy or financial balance per area (MJ ha^{-1} or US\$ ha^{-1}).

The ratio between $TCMRE$ and $EFB_{row\text{-}metre}$ (Eq. (21)) is the length of a row necessary to pay for the manoeuvre. When a full row length is shorter than this, the respective row is considered unprofitable.

$$EMCRL = \frac{TCMRE}{EFB_{row-meter}} \tag{21}$$

where $EMCRL$ is the equivalent manoeuvre cost in row length (m).

2.4. Scenarios for calculating the impact of types of manoeuvre

Planting and cultivating present suitable options for replacing costly manoeuvres by U-turns (skipping rows) where the aim is to reduce manoeuvring time and reduce manoeuvring space. In this work scenarios were set-up with the values shown in Table 5 using the manoeuvring equations. A fixed number of 6 w and 3 w were used for skipping rows for the planting and cultivating operations respectively.

Figure 8 illustrates the relationship between manoeuvring space, time and cost of row-length for three manoeuvres with a sugarcane carrier: Ω-turn, T-turn and P-turn. The sugarcane rows in green (in the web version) shift into grey after a transversal line. The length of the grey lines represents an equivalent time in row-length-cost for the manoeuvres.

A study was carried estimating the impacts of these turns in the full cost of the manoeuvres (manoeuvre space + $EMCRL$) using the parameters presented in Table 6. The time and space parameters were obtained for: w of 1.5 m (working width); an implement width (for road turning) of 3 m; forward steering, rearward speed and forward straight distance of 1.5 m s^{-1}, 0.6 m s^{-1} and 2 m s^{-1} respectively; a general $D\text{-}MDS$ arbitrarily set to 20 m.

The variables to be simulated from the data in Table 6 were subject to comparison in the set of distinct economic revenue scenarios pointed out earlier to observe their impact on the manoeuvring space cost. The model was build using the equations above using a Microsoft Excel™ spreadsheet in order to answers the research questions posed.

3. Case studies, model sensitivity and discussion

3.1. Machine and field parameters influencing manoeuvres

The effects of two variables in the turning patterns were studied: turning radius (r) and angle of deviation from a perpendicular border (θ). The width of the operation (w) was not studied, given the difficulty of significantly enlarging the width of implements used in the sugarcane system.

In Fig. 9, Ω-Turns are limited to be performed up to a 60° angle of θ inclination, and above this another type of turn would follow (a "Hook-turn" according to Jin & Tang, 2010). In practice, for sugarcane, P-turns would replace Ω-Turns for high θ inclination. A value of 10° was assigned to θ for graphs 'b' and 'd'; and an r of 7 m was assigned for graphs 'a' and 'c'.

For T-turns the DBA was set in 9 m (trailed vehicle). The DBT for the U-turns was the minimum distance of skipping rows considering r and w. The $D\text{-}MDS$ was set in 20 m.

The snake-shape in the graph for U-manoeuvres in Fig. 9d occurs because of the effect of skipping rows, in which the increase in turning radius may lead to an immediate need to skip one more w.

The choice for P-turns for carrier-wagons can be understood regarding the low space demand for manoeuvre that it presents compared to the Ω-turn (for manoeuvres into adjacent rows). This additional space needed can be generically rounded and averaged to 9 m for along values of r.

The benefits of using U-turns decreased for large θ values. This observation was also made by Spekken and de Bruin (2013). Despite P-turns being the most common manoeuvre for harvesting (i.e. for the carrier-wagons), nonetheless they

Table 5 – Turning types and their respective demands obtained for two operations.

	Ω-turn		U-turn		T-turn	
	Time (s)	Space (m)	Time (s)	Space (m)	Time (s)	Space (m)
Planting[a]	46.8	22.1	25	10.9	80.5	10.9
Cultivating[b]	20.2	12.5	10.5	6.8	24.5	6.8

[a] Implement pulled by tractor's traction bar. Length of a manoeuvre calculated for planting with an r of 8 m; forward and rearward velocity of manoeuvring of 1.2 m s^{-1} and 0.6 m s^{-1}, DBA of 13 cm and a total stopped time of 8 s.

[b] Implement three point attached to the tractor. Length of a manoeuvre calculated for planting with an r of 4.5 m; forward and rearward velocity of manoeuvring of 1.5 m s^{-1} and 1 m s^{-1} respectively, DBA of 3 m and a total stopped time of 6 s.

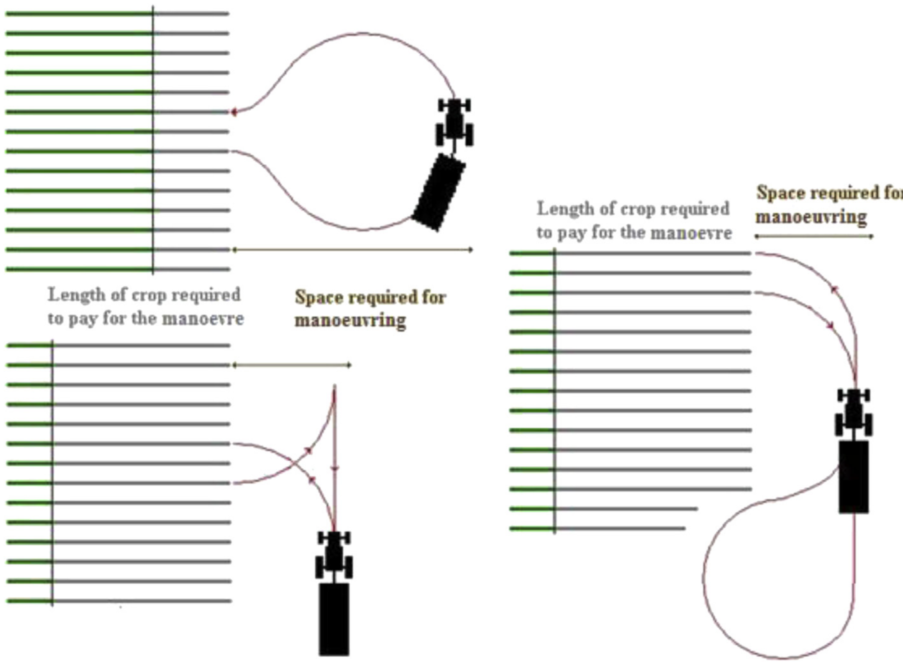

Fig. 8 – Three distinct types of manoeuvres and their space and time equivalent costs.

are the most time consuming of manoeuvres. Even when the *MDS* was closest to the transport unit (*D-MDS* equal to 0), the manoeuvre time was still 69 s.

3.1.1. *Time impact of manoeuvring*

The sensitivity of the time impact of manoeuvres in sugarcane harvest was obtained simulating increasing *ARL* and TC. The operation speed was set on 1.575 m s^{-1} (Salvi et al., 2010). Results are shown in the graph of Fig. 10.

A range of values between 2.2 % and 38.7 % for the non-working time due to headland manoeuvres was found during harvesting. The analysis still did not consider that rows can be shorter than the 300 m, mainly in corners of fields and obstacles. Regarding time spent, in the literature this extended to 2 min (120 s in the graphs). Since short rows are almost unavoidable in many fields, options for efficiency were limited by the speed manoeuvring time or by avoiding these regions.

A standard scenario was set for the model to calculate the *CMRE*. The variable settings can be seen in Table 7.

The costs found for a single turn was of 93.29 MJ and US$ 4.45. The harvest operation comprised the majority of the costs with 92.6 and 93.0% of the respective energy and financial costs in the listed operations.

3.1.2. *Manoeuvre cost per area*

In the given CRME scenario, with a standard *ARL* and row width 300 m and 1.5 m respectively, the cost of manoeuvring per area was of 2073 MJ ha^{-1} and 98.9 US$ ha^{-1}. A sensitivity analysis was applied into the model by varying a of row-length distance in a range between 50 and 1000 m, retrieving the respective turning costs.

Figure 11 shows the impact of manoeuvres in short rows which may surpass the economic return (average of five years in Table 4) in rows shorter than 50 m. The figure also shows that continuous efforts to lower manoeuvring costs by increasing the row length give a decreasing benefit. This must be taken into account because longer rows can lead to a problem with machine servicing, when they reach their product capacity (i.e. carrier baskets are full or spraying and fertilising tanks are empty) at locations far from the roads where these can be unloaded/replenished. Thus the overall efficiency can be rather damaged than improved by long rows. Benedini and Conde (2008) suggested the length of the row to

Table 6 – Input data for comparison of three turning types and three carrier types to quantify cost of manoeuvring by row-length.

Carrier type	Turning radius (m)	Ω-turn		T-turn		P-turn	
		Space (m)	Time (s)	Space (m)	Time (s)	Space (m)	Time (s)
Self-propelled carrier[a]	5	14.5	23.6	7.4	43.0	7.6	53.8
Single wagon[b]	7.5	21.3	35.8	10.3	57.1	10.9	71.4
Double wagon	10.8	23.6	48.1	na[c]	na[c]	15.2	89.0

[a] Distance between axles (*DBA*) of 5 m.
[b] Distance between axles (*DBA*) of 9 m.
[c] ‘Not applicable’ – double wagon carrier unlikely uses reverse manoeuvring due to the difficulty to drive it rearwards.

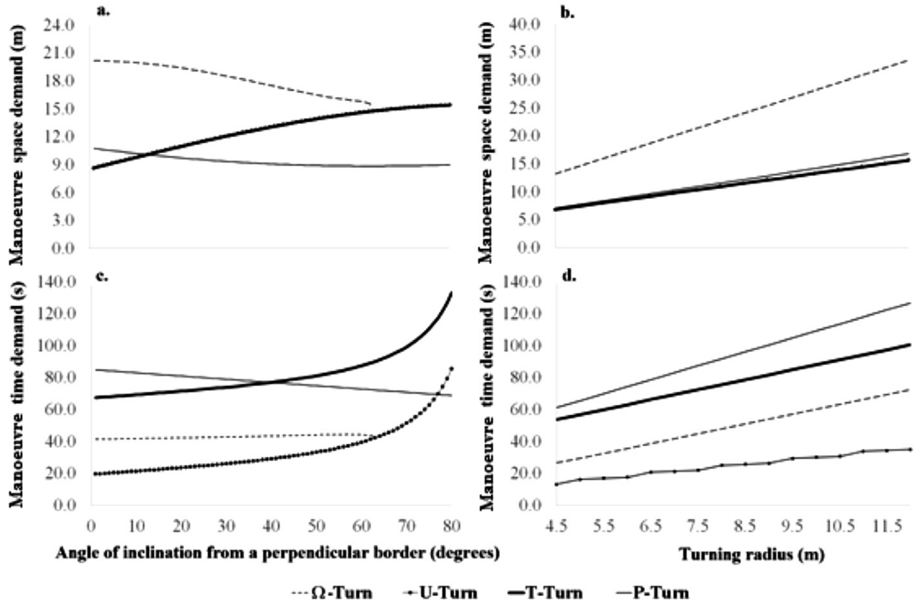

Fig. 9 – Sensitivity analysis of the effects of the angle and turning radius in the manoeuvring length and space.

be within 500–700 m, the benefit for extending the row from 700 m to 1000 m was shown to yield a benefit of only 9.38 US$ ha^{-1} for manoeuvring. Considering that the costs of servicing operations significantly surpass the non-servicing operations (such as soil tillage which occurs every five years), studies directed towards the latter were not carried out.

For many sugarcane fields when roads do not limit the length of row, but cut through it, no manoeuvre is required and fully loaded transport units can just steer onto the roads. In such cases extending row length can continue yielding profits if the area is properly segmented by crossing roads.

Figure 12 quantifies the benefit in increasing coverage width of the sugarcane rows by decreasing the number of turns and the respective spatial turning costs. Above the width of 1.8 m the crop is herein considered to be implanted in twin-rows and the planting and cultivating operations can no longer cover two rows (i.e., 1.9 m width), slightly increasing the overall manoeuvring time. Increasing width, despite its benefit in reducing manoeuvring costs, will also influence the

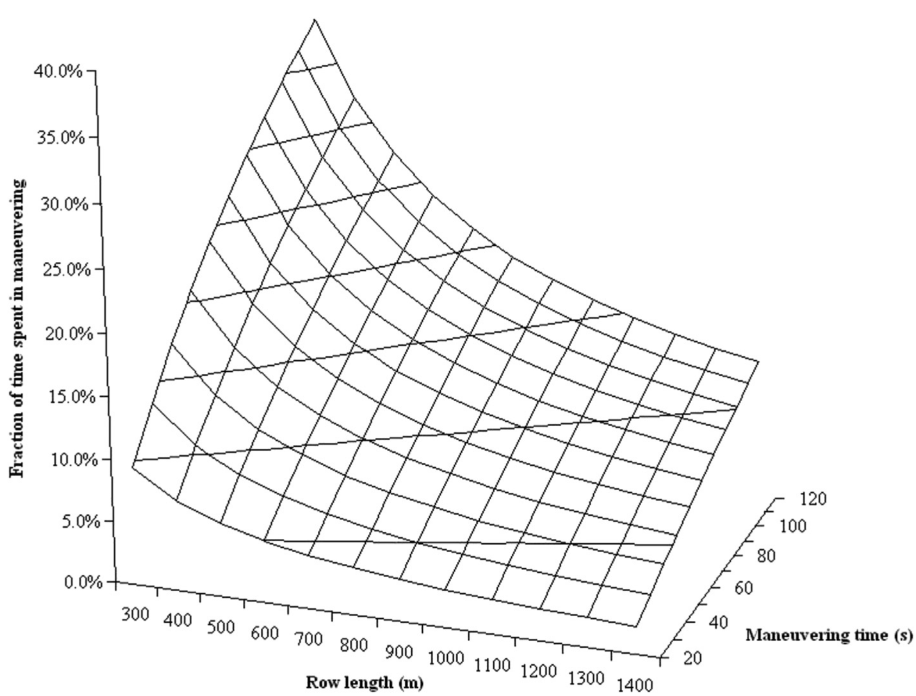

Fig. 10 – Fraction of time spend in manoeuvring a sugarcane harvester for its overall efficiency.

Table 7 – Standard setting parameters used for calculation of *CMRE* and its respective costs.

	NRC	*F*	Time energy cost (MJ s^{-1})	Time economic cost (US\$ s^{-1})	Manoeuvre time (s)	*CMRE* (MJ)	*CMRE* (US\$)
Planting	2	0.2	0.327	0.02	80.5	2.63	0.17
Cultivating	2	1	0.306	0.01	24.5	3.75	0.12
Spraying	12	1	0.311	0.01	20	0.52	0.02
Harvesting	1	1	0.971	0.05	89	86.4	4.14

servicing of machinery, mainly the sugarcane carriers, because it will fill the basket in a shorter harvested distance. An optimisation between crop yield, machine capacity, width of coverage and row length poses a topic for further study. Considering the standard scenario of *ARL* and *CMRE*, increasing *ARL* in 150 m yields savings equivalent to reducing the manoeuvring times of planting and harvesting in 30 s.

3.1.3. *Manoeuvring cost within sugarcane energy and economic balance*

In a standard *TCMRE* scenario, the fraction of costs related to energy and economic perspectives are displayed in Table 8. The energy input represents 10.7% of the crude output, contrasting with economic evaluation where the input represents 85.1% of the crude output (average over 5 years). It strongly indicates that the full economic input is not so much related to the financial costs of raw material (iron, rubber, fuel, etc) but rather to the cost of the embedded technology (or embodied knowledge cost). This suggests that the sustainability of sugarcane crop production is more fragile in terms of economic balance rather than its energy balance.

In Table 8, the higher manoeuvring proportion of the energy cost compared to economic in the total input shows the impact of the embodied knowledge cost in the majority of other economic costs of sugarcane (administration, land lease, technology patents, etc). Despite the small fraction of manoeuvres in the economic total input, these can have a significant weight in the profit (which is less than 15% of the economic crude output). For example, a cost of manoeuvring per area of 98.9 US\$ ha^{-1} (found for a standard scenario) represents a fraction of the 20% of the income (when considering the income Table 4 of net revenue, averaged over 5 years).

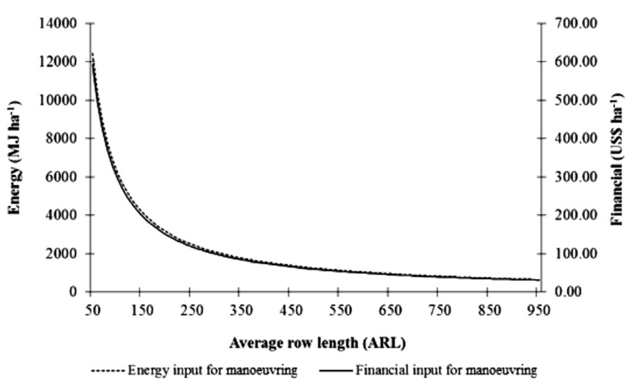

Fig. 11 – Cost of manoeuvering per area with increasing row length.

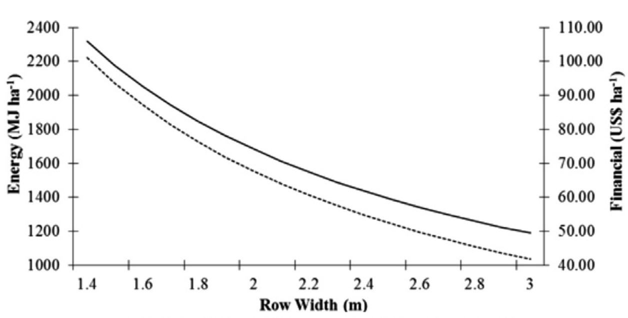

Fig. 12 – Costs of manoeuvring per area with increasing coverage capacity of machines.

3.1.4. *Cost impact of a manoeuvre translated in length of crop-row*

The net output of the crop translated into length of crop-row can be seen in Table 9. A significant difference is found among the harvest sequences. While the net output of energy of fifth harvest represents 55.2% of the first, economically this value drops to 14.8%. The data provided in Table 10 indicates the length required for the crop to pay for its manoeuvring costs. The most optimistic scenarios of profitability still require 30.5 m of crop row.

Figure 13 shows a real spatial dataset of pre-planned sugarcane rows. This dataset represents a subset field located in the corner of a farm containing some obstacles. The rows in red are shorter than 50 m (threshold rounded from the results in Table 10, from the average length of tracks a profitable row need) which are located in edges of the fields and between obstacles, these represent 22.8% of the rows (and manoeuvres) in the dataset, but only 4.2% of the total area.

3.2. *Output of manoeuvring costs in different scenarios*

Using the standard scenario of 300 m of average row length, an analysis was done comparing the costs of turning types

Table 8 – Fraction of manoeuvring in the total sugarcane input cost for the standard *CMRE* scenario.

Annual harvest sequence from ratoon	Yield (Mg ha^{-1})	Fraction of the total input related to manoeuvres (%)	
		Energy	Economic
1	106	8.3%	3.6%
2	84	10.5%	4.5%
3	76	11.6%	4.3%
4	66	13.4%	4.8%
5	58	15.3%	5.2%
Average	78	11.8%	4.5%

Table 9 – Energy and economic balance of a metre-row of sugarcane found.

Harvest sequence	Yield ($Mg\ ha^{-1}$)	Revenue per length of row	
		Energy ($MJ\ m^{-1}$)	Economic ($US\$\ m^{-1}$)
1	106	31.36	0.14
2	84	24.92	0.11
3	76	22.58	0.05
4	66	19.65	0.04
5	58	17.31	0.02
Average	78	23.16	0.07

Table 10 – Equivalent length of rows required to pay for the cost of manoeuvres using different scenarios of economic net revenue.

Harvest sequence	Energy	Economic scenarios of net output			
	Standard	Standard	+50%	+75%	+100%
	Equivalent row length to cover manoeuvre cost (m)				
1	2.21	32.6	21.7	18.6	16.3
2	2.78	39.0	26.0	22.3	19.5
3	3.06	81.7	54.5	46.7	40.8
4	3.52	110.0	73.3	62.8	55.0
5	4.00	228.0	152.0	130.3	114.0
Average	2.99	62.0	40.6	34.8	30.5

feasible during the planting and cultivating operations. The manoeuvring time costs were extracted from the parameters given in Table 5, with the frequency of 0.2 and 1 times per year for the planting and cultivating operations (Table 7). The space cost was obtained by an equivalent of spatial to row-length in the standard scenario (Table 9). The results are displayed in Table 11.

In the three scenarios studied the economic costs the T-turns almost reached the cost of the space demanding Ω-Turns. Also the savings in the use of U-turns, for large areas covered, may provide savings that allow the investment in guidance systems for skipping rows. The change from T-turns to skipping rows can produce savings of 88 $MJ\ ha^{-1}$ and 4.15 $US\$\ ha^{-1}$ for both operations considered.

3.2.1. *Impact of enlarging manoeuvre space*

The model result of the variables proposed in Table 6 for manoeuvring and carrier types is given in Table 12. The loss of area turning a machine in a space consuming manoeuvre (such as the Ω-turn) is still more profitable because of its time savings benefit; and this was found for any of the scenarios tested. The current belief that narrow roads reduce area loss leading to financial benefit is therefore questioned. Also savings can be seen for using self-propelled and single-wagon carriers which can reduce considerably the necessity of installing wide roads for turning.

If certain manoeuvres require wider roads by taking this space from productive areas, the time savings benefit can still exceed the financial output that the crop can produce. In a standard scenario, from an economic perspective, every second of harvest manoeuvring is the equivalent to 0.64 m of crop harvested in single row, 0.40 m of crop harvested in twin row and 0.32 m of crop harvested in double row.

The methodology used here is applicable for other crop growing systems where high manoeuvring costs are expected, but is less likely to be useful for wider machine coverage and lower biomass intake.

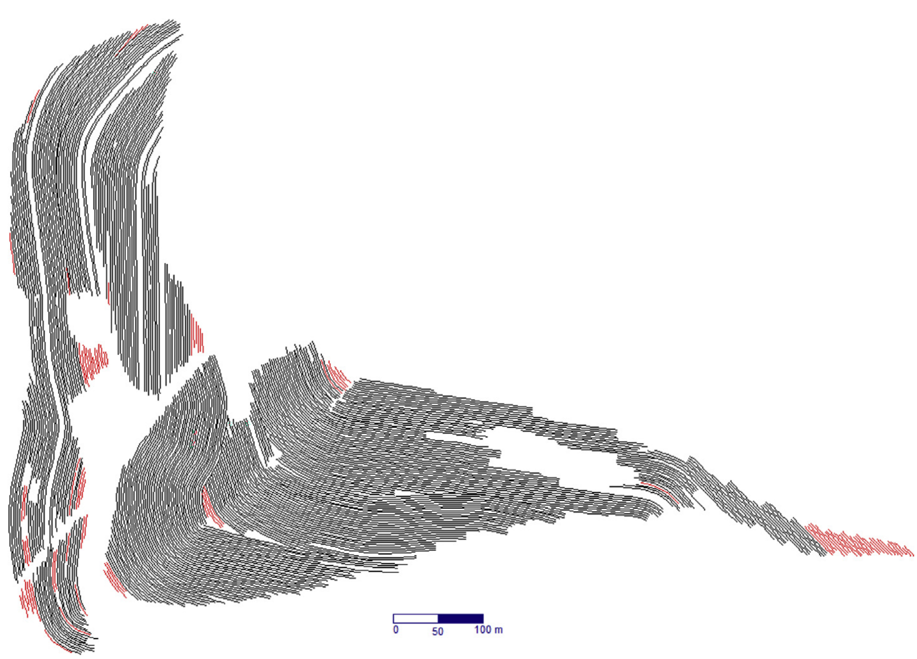

Fig. 13 – Spatial pre-planned tracks for sugarcane rows. Rows in red are too short to pay for the cost of the headland manoeuvre. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 11 – Cost impact obtained for the three manoeuvring types considering their space and time demanded for turning.

	Cost for loss of cropped area		Cost of manoeuvring time		Total cost	
	Energy (MJ ha^{-1})	Economic (US$ ha^{-1})	Energy (MJ ha^{-1})	Economic (US$ ha^{-1})	Energy (MJ ha^{-1})	Economic (US$ ha^{-1})
Planting						
Ω-turn	511.8	3.18	33.9	2.20	545.7	5.38
U-turn	252.4	1.57	18.1	1.18	270.5	2.75
T-turn	252.4	1.57	58.4	3.78	310.8	5.35
Cultivating						
Ω-turn	289.5	1.80	68.8	2.23	358.3	4.03
U-turn	157.5	0.98	35.7	1.16	193.2	2.14
T-turn	157.5	0.98	83.41	2.71	240.91	3.69

4. Conclusions

The cost of manoeuvring in sugarcane was calculated by a number of variables taking into account machine hourly cost, both in terms of energy and economic. For the standard scenario energy and economic costs per manoeuvre were 93.3 MJ and US$ 4.45, respectively, for which harvesting comprises the majority of the costs. This is in agreement with other authors on the major impact of harvesting in the production of the sugarcane.

The cost per area for manoeuvring is dependent on width of coverage and length of rows, taking a set of standard values for these, the cost of manoeuvring per area was found to be 2073 MJ ha^{-1} and 98.9 US$ ha^{-1}. Efforts to increase the length of the rows will provide decreasing savings, suggesting the row lengths should be limited to 500–700 m regarding the logistics of transporting units. Increasing coverage width, which is usually limited by harvesting machines, showed a potential to decrease manoeuvring costs.

Table 12 – Four scenarios of summed time and space economic costs for three manoeuvring types and three sugarcane carrier machines.

Carrier type	Summed space and time cost for manoeuvring (US$)		
	Ω-turn	T-turn	P-turn
Standard scenario			
Self-propelled carrier	3.22	4.48	5.49
Tractor + single wagon	4.84	5.99	7.34
Tractor + double wagon	6.13	–	9.27
Net output + 50%			
Self-propelled carrier	3.75	4.75	5.76
Tractor + single wagon	5.61	6.36	7.74
Tractor + double wagon	6.99	–	9.82
Net output + 75%			
Self-propelled carrier	4.02	4.89	5.90
Tractor + single wagon	6.00	6.55	7.94
Tractor + double wagon	7.42	–	10.10
Net output + 100%			
Self-propelled carrier	4.28	5.02	6.04
Tractor + single wagon	6.39	6.74	8.14
Tractor + double wagon	7.85	–	10.38

Manoeuvres may comprise a small fraction in the final production costs, but they have a large impact on the final economic revenue. The high positive energy balance of the sugarcane crop indicates that the fragility of the production system occurs because of economic reasons.

The minimum length required to pay for a headland manoeuvre in a standard set scenario was of 62 m on average. More optimistic scenarios of economic revenue still demand more than 30 m of row length to start yielding economic profitability.

A real-life case-study site showed a number of pre-planned tracks that would be composed by 18.7% of economic unprofitable tracks in a standard scenario. The use of different turning patterns for planting and cultivating operations pointed to savings summing 88 MJ ha^{-1} and 4.15 US$ ha^{-1}. The cost implementing guidance systems in the machinery to orient the row skipping was not computed.

The scenarios of cane-carriers types, manoeuvre types and revenue obtained showed that the use of short width roads results in more cost than benefit. Optimised solutions were found with use of carriers with short turning radius and roads wide enough for Ω-turns.

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