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OPTIMAL MOMENT TO CHANGE PRESSURE REGULATOR AND SPRAYER KIT ON CENTER PIVOT IRRIGATION MACHINES: A THEORETICAL PROPOSAL

Ramón Pérez Leira[1], Rodrigo Máximo Sánchez-Román*[2], José Antonio Frizzone[3]

[1] CNPq fellow. Associate professor at Hydraulic Investigations Center. Instituto Superior Politécnico "José Antonio Echeverría" (ISPJAE). E-mail: rpleira@cih.cujae.edu.cu

[2] Professor at São Paulo State University, Agricultural Science College (UNESP-FCA), Botucatu, São Paulo (SP), Brazil, e-mail: rmsroman@fca.unesp.br

[3] Full Professor at Escola Superior de Agricultura "Luiz of Queiroz", University of São Paulo (ESALQ-USP). E-mail: frizzone@esalq.usp.br

1 ABSTRACT

A theoretical model was developed in order to determine the optimal moment for substituting the sprayer and pressure regulator kit on a center pivot irrigation machine. The model is based on the hypothesis that pressure regulator and sprayer deterioration decrease irrigation uniformity. To compensate the deficit that happens at under irrigated areas, an increase on irrigation depth is required. The model considers: additional water consumption and energy costs, maintenance and labor costs, as well as yield losses associated with under or over irrigated areas. The sum of all these components is compared to buying and installing a new spray kit cost, allowing the farmer to decide the best moment to renovate the sprayer and pressure regulator kits on a center pivot irrigation machine based on economic criteria.

Keywords: pivot, irrigation, mathematical model, costs, efficiency

2 INTRODUCTION

Easy automation, low labor requirement and the possibility of low pressures demand have been the main reasons that have make possible the quick expansion of center pivot irrigation machines (CPIM) around the world (Lyle & Butler, 1980; Bordousky et al., 1992; Tarjuelo, 1999). During the last four decades, many studies have attempted to substitute other irrigation techniques for center pivots (Wood et al., 2007) and to improve irrigation making it more efficient and sustainable under different climate conditions, soils and crops.

However, in the last 20 years, water and energy availability have decreased considerably on the planet. This has compelled designers and farmers to look for alternatives to reduce water and energy consumption associated to CPIM irrigation. That is how LEPA devices showed a notable increase in uniformity, irrigation efficiency and a more rational use of the energy (Gilley & Mielke, 1980; Sourell, 1985; Glenn et al., 1994; Tarjuelo, 1999). Nevertheless, these advantages, according to King & Kincaid (1997) did not find an economic return due to installation expenses and circular planting requirement. Most of the studies about pivot irrigation quality are based on Hermann & Hein's Uniformity Coefficient –UC_h- (1968) although Bremond & Molle (1995) demonstrated that UC_h is not as sensitive to disturbances during irrigation as Christiansen's Uniformity Coefficient (CU). Pérez et al. (2003), after evaluating a group of

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CPIM, concluded that a single indicator is not enough to determine irrigation quality, and the factors that affect irrigation uniformity in CPIM, more often are related to technical damage and incorrectly assembled nozzles and pressure regulators. Allen (1990) made a significant contribution to CPIM hydraulic design theory when incorporate agronomic approaches to its design. Regarding spray nozzles, Keller & Bliesner (1990), Abo-Ghobar (1992), Kinkaid (1996) and Pérez et al. (2001) agree on the advantages of placing the emitters at 1.0 m above soil surface rather than 2.30 m. Omary & Sumner (2001) starting from laboratory evaluations, performed simulations in which they obtained average uniformity coefficients of 98.4%. Faci et al. (2001) found obvious differences of rain quality produced by fixed spray nozzles with regard to rotating ones. Sourell et al. (2003), from simulations carried out with rotating irrigation devices and different conditions, found a CU above 87%, with a mean value of 91.8%.

In a study carried out by Al-Kufaishi et al. (2006) on the effect of variable application depths on uniformity, it was found out that water loss was greater when constant depths were applied. Research developed in the last decade, analyzing the economic benefits of optimal irrigation have concluded that irrigation efficiency can increase income considerably (Frizzone et al. 1997; Sousa et al. 1998; Frizzone 1998; Heinemann et al. 2000; Andrade et al. 2001; Heineman et al. 2001; English et al. 2002; Gorantivar and Smouth 2003; Frizzone 2003; Miranda & Pires 2003; Montero et al. 2004; Perry et al. 2004; Brennan 2007).

Ribeiro (2001) studying the lifespan of a pressure regulator confirmed that up to 6000 hours was an invariable life span. Evaldo et al. (2001) determined that the uniformity coefficient and the irrigation depth diminish after using the sprinkling kit for more than six years. However, farmers hesitantly ask themselves the following question: Until when is it profitable to irrigate with these devices after having accumulated thousands of hours of use?

It is supposed that, the decrease in irrigation uniformity caused by the worn sprinkling kit would force the irrigator to over irrigate to compensate for the deficit in under irrigated. This would certainly impact irrigation operational costs. Based on this hypothesis, this paper has the objective of developing a theoretical model that defines approaches and variables to be considered to decide the optimal moment to change the pressure regulators kit on a pivot.

3 MATERIAL AND METHODS

To apply the methodology proposed here, it is necessary to carry out a pluviometric evaluation at the beginning of the irrigation season with new pressure regulator and sprayer kits (or with less than 2000 hours of use). It is also required annual planted and harvested under irrigation crop yield records. The optimal moment for changing the pressure regulator and sprayer kit on a CPIM was defined using economic approaches. To perform this analysis, the possible incidence of fixed and variable costs was considered. Fixed costs (FC) are: price of pressure regulators and nozzles kit (PMR) and installation cost of the kit on the CPIM (CIM). Variable costs (VC) under consideration are: additional energy consumption cost (AECC); additional water consumption cost (AWCC); additional labor consumption cost (ALC); additional maintenance cost (AMC) and yield losses cost (YLC).

Taking into account that the fixed costs (FC) are a constant value and that the sum of all the variable costs (VC) are influenced on decisions taken daily, it can be stated that:

FC = PMR + CIM (1)

VC = AECC + AWCC + ALC + AMC + YLC (2)

If it is considered for this analysis that the change of the kit is only economically feasible once FC < VC, then it can stated that the condition of no substitution of the pressure regulators and nozzles kit would happen when FC ≥ VC. Therefore,

PMR + CIM ≥ AECC + AWCC + ALC + AMC + YLC (3)

Starting from this inequality, each one of their parameters is determined. To determine fixed costs is only necessary when considering the supplier's offers. This is not the objective of this work. The variable costs could be determined from the following approaches:

Additional energy consumption cost (AECC). The AECC would be determined using the equation proposed by Marques (2005) for an electric engine:

$$Cab = (FDa + FCa)\left(\frac{0.92}{\cos\varphi}\right)(1 + ICMS) \quad (4)$$

where Cab is the pumping annual cost (R\$); FDa is the annual power demand bill (R\$); FCa is the annual power consumption bill (R\$); ICMS is the tax on circulation of goods and services in the region (R\$); and cos φ is the power factor.

$$D = 0.736 \cdot P \quad (5)$$

where D is the demands hired (kW) and P is the engine power (CV).

In Brazil, the demand and consumption costs are determined, for the so called 'Grupo A' consumers, considering three rates. These consumers have to have an installed power requirement of at least 50 kW and less than 2500 kW. The rates are: i) Conventional rate: applied when tension is less than 69 kV and demand no less than 500 kW; ii) Blue rate: applied when tension is equal or superior to 69 kV and units with tension less than 69 kV and power demand greater than 500 kW; and iii) Green rate: offered optionally to consumers with a tension less than 69 kV and starting demand of 50 kW.

Regarding these three rates, Marques (2005) proposed the following equations:

i) For the conventional rate.

$$\mathrm{FDm} = (\mathrm{Tdm} \cdot \mathrm{D}) \quad (6a)$$

$$\mathrm{FDa} = \sum_{\mathrm{month}=1}^{12} \mathrm{FDm} \quad (6b)$$

$$\mathrm{FDm} = \mathrm{TCc}[\mathrm{Hd}(1 - \mathrm{fd}) + \mathrm{Hs}] \cdot 0.736 \cdot \mathrm{P} \quad (7a)$$

$$\mathrm{FCa} = \sum_{\mathrm{month}=1}^{12} \mathrm{FCm} \quad (7b)$$

where FDm is the monthly power demand bill (R$); Tdm is the demand rate (R$ kW^{-1}); FDa is the annual power demand bill (R$); FCm is the monthly power consumption bill (R$); TCc is the conventional consumption bill (R$ kW^{-1}); Hd is the operation hours with discount (h); Hs is the operation hours without discount (h); Fd is the public legislation discount factor; and FCa is the annual power consumption bill (R$).

ii) For the blue rate.

$$FDm = [(Td_{azp} \cdot Dp) + (Td_{azf} \cdot Df)] \quad (8)$$

$$FCm = [TC_{azuf}(Hd(1 - fd) + Hsf) + TC_{azup} \cdot Hp] \cdot 0.736 \cdot P \quad (9)$$

$$FCm = [TC_{azsf}(Hd(1 - fd) + Hsf) + TC_{azsp} \cdot Hp] \cdot 0.736 \cdot P \quad (10)$$

where Tdazp is the blue demand charge at peak demand (R$ kW^{-1}); Tdazf is the blue demand charge in schedule out of peak (R$ kW^{-1}); Dp is the demand requested at peak demand (kW); Df is the demand requested out of peak demand (kW); TCazuf is the blue consumption charge out of peak demand during the wet season (R$ kW^{-1}); Hsf is the operation hours out of peak demand without discount (h); Hp is the operation hours during peak demand (h); TCazup is the peak demand blue consumption charge during the wet season (R$ kW^{-1}); TCazsf is the peak demand blue consumption charge during the dry season (R$ kW^{-1}) and TCazsp is the peak demand blue consumption charge out of the dry season (R$ kW^{-1}). The total annual power demand bill will be computed with Eq. (6b) and total annual power consumption bill with Eq. (7b).

iii) For the green rate.

$$FDm = (Tdv \cdot D) \quad (11)$$

$$FCm = [TC_{vfu}(Hd(1 - fd) + Hsf) + TC_{vpu} \cdot Hp] \cdot 0.736 \cdot P \quad (12)$$

$$FCm = [TC_{vfs}(Hd(1 - fd) + Hsf) + TC_{vps} \cdot Hp] \cdot 0.736 \cdot P \quad (13)$$

where Tdv is the green demand charge (R$ kW^{-1}); Hp is the operation hours during peak demand (h); Hsf is the operation hours out of peak demand without discount (h); TCvfu is the green consumption charge out of peak demand during the wet season (R$ kW^{-1}); TCvfs is the green consumption charge out of peak demand during the dry season (R$ kW^{-1}); TCvpu is the peak demand green consumption rate during the wet season (R$ kW^{-1}); TCvpu is the peak demand green consumption rate during the dry season (R$ kW^{-1}). Total annual power demand bill will be computed with Eq. (6b) and total annual power consumption bill with Eq. (7b).

For diesel engines it was considered the expression proposed by Marques (2005):

$$Cab = Co \cdot P \cdot Cs \cdot 0.0047 \cdot \sum_{month=1}^{12} H \quad (14)$$

where Cab is the pumping annual cost (R$); Co is the diesel fuel cost at the property (R$); Pot is the engine power (CV); Cs is the engine specific consumption (L CV^{-1} h^{-1}); and H is the operation hours per month (h).

Additional water consumption cost (AWCC). To compute AWCC the following expression was considered:

$$WCC = Q \cdot H \cdot Pa \tag{15}$$

where WCC is the water consumption cost (R$); Q is the CPIM flow rate (m^3 h^{-1}); Pa is the water price (R$ m^{-3}); and H are the annual operation CPIM hours (h).

Additional labor cost (ALC). To determine the ALC, the expression proposed by (Marques 2005) based on labor conditions in Brazil was considered:

$$ALC = \sum_{irrigation_{days}=1}^{n} \left[\frac{S}{240}\right] \cdot \left[1 + \left(\frac{Holidays + T13 + INSS + IT}{100}\right) \cdot (Hr)\right] \tag{16}$$

where S is the monthly wage (R$); Holidays is the payment for holidays as a wage percentage (%;) T13 is the 13th wage payment as a percentage of salary (%); INSS is the payment to the INSS (National Social Security Institute) as a wage percentage; IT is the payment to INSS for the 13th wage as a wage percentage (%); and Hr is the hours required to apply an irrigation (h).

Additional maintenance cost (AMC). To compute AMC, the expression proposed by Marquez (2005) was considered:

$$AMC = \frac{Tm \cdot Ps}{100} \tag{17}$$

where Cam is the annual maintenance cost (R$); Tm is the annual maintenance rate (%); and Ps is the acquisition and installation price for irrigation equipment (R$).

The life cycle and the annual maintenance rates shown at Table 1 (Zocoler, 2003), developed for 2000 hours annual operation time, was also used as reference.

Table 1. Life cycle and maintenance rates for center pivot irrigation machines main components

Irrigation system component	Life cycle (years)	Maintenance rates (% Initial Value)
Fixed Sprinklers	7-10	5.0-8.0
Centrifugal pump	16-25	3.0-5.0
Pumping Station (structure)	20-40	0.5-1.5
Diesel engine	10-20	5.0-8.0
Electric engine	20-25	1.5-2.5
Steel pipe underground	15-25	0.25-0.50
Surface Galvanized Steel Pipe	10-20	1.0-2.0

Fonte: Zocoler, 2003

Yield losses Cost (YLC). The yield losses were modeled from the expressions proposed by Wu & Barragán (2000):

$$y = y_m - \left(\frac{y_m \cdot K_y}{2b}\right)\left(X - 2a + \frac{a^2}{X}\right) \qquad (18)$$

where y_m is the maximum possible crop yield having full water availability (Kg ha^{-1}); K_y is the crop sensibility to irrigation (adimensional); and a & b are the adjustment parameters determined by Wu (1998) as:

$$CV = 0.29b \qquad (19a)$$

$$CU = 1 - 0.25b \qquad (19b)$$

$$a = 1 - 0.5b \qquad (20)$$

where CV is the coefficient of variation; CU is Christiansen's Uniformity Coefficient; X is the relative irrigation rate to reach maximum yield (decimals), and

$$X = \frac{W_m}{Q \cdot T} \qquad (21)$$

where Wm is the required water volume to obtain maximum yield –Ym- (m^3); Q is the irrigation system flow rate (m^3 h^{-1}); and T is the irrigation time (h).

4 RESULTS AND DISCUSSION

Determination of Additional Energy Consumption Cost (AECC). To determine the cost due to the additional consumption of energy (AECC), the following relationship is proposed:

$$AECC = AECCKv - AECCKn \qquad (22)$$

where AECCKv is the energy consumption cost with the old Kit (R$); and AECCKn is the energy consumption cost with the new Kit (R$).

The value of AECCKn for electric engines is computed from the sum of the demand and consumption bills obtained by the expressions 6 through 13, being:

$$AECCKn = (FDa_{TC} + FCa_{TC} + FDa_{TA} + FCa_{TA} + FDa_{TV} + FCa_{TV})\frac{0.92}{\cos\varphi}(1 + ICMS) \qquad (23)$$

where all variables have already been defined by Eq. 6b and 7b, except for $[\ ]_{TC}$ for conventional rate; $[\ ]_{TA}$ for blue rate; and $[\ ]_{TV}$ for green rate.

To compute AECCKv Eq. 23 could be used but it requires a factor to consider the extra irrigation time required. This factor takes into account the under irrigated areas, which are associated to lack of uniformity due to worn pressure regulators and emitters. To do so, it is necessary to know how much time would be necessary to guarantee that the mean depth collected (MDC) after a hydraulic evaluation be equal to the crop water requirements (CWR).

The increase in irrigation time can be expressed as percentage of irrigation time increase (ITr) and determined by:

$$ITr = \frac{TrKv}{TrKn} \tag{24}$$

where ITr is the irrigation time increase (decimals); TrKv is the irrigation time required with the old sprayer kit (h); TrKn is the irrigation time required with the new sprayer kit (h). These time irrigation times are defined by Eq. 25 and 26.

$$TrKv = \frac{CWRbi \cdot Tmin}{Dmin} \tag{25}$$

and,

$$TrKn = \frac{CWRb \cdot Tmin}{Dmin} \tag{26}$$

where CWRbi is the gross irrigation depth increased to compensate problems in irrigation uniformity (mm); CWRb is the gross irrigation depth required by the crop (mm); Tmin is the time required by the CPIM to apply an irrigation depth at maximum speed (h); and Dmin is the minimum depth of irrigation applied by the CPIM at maximum speed (mm). Additionally,

$$CWRb = \frac{CWR}{Ea} \tag{27}$$

where CWR are the crop water requirements (mm); and Ea is the application efficiency (decimals).

Once the value of ITr is well known it can be stated that:

$$AECCKv = (FDa_{TC} + FCa_{TC} + FDa_{TA} + FCa_{TA} + FDa_{TV} + FCa_{TV})ITr\frac{0.92}{\cos\varphi}(1 + ICMS) \tag{28}$$

substituting 23 and 28 in 22 and simplifying, we obtain:

$$AECC = (FDa_{TC} + FCa_{TC} + FDa_{TA} + FCa_{TA} + FDa_{TV} + FCa_{TV})\frac{0.92}{\cos\varphi}(1 + ICMS)(ITr - 1) \tag{29}$$

For diesel engines the AECC is determined by:

$$AECC = CabKv - CabKn \tag{30}$$

where CabKv is the annual pumping cost using old sprayer kits (R$); and CabKn is the annual pumping cost using new sprayer kits (R$). They are defined by Eq. 31a and 31b.

$$CabKn = Co \cdot P \cdot Cs \cdot 0.0047 \cdot \sum_1^{12} H \quad (31a)$$

$$CabKv = Co \cdot P \cdot Cs \cdot 0.0047 \cdot \sum_1^{12} (ITr \cdot H) \quad (31b)$$

then,

$$AECC = CabKv - CabKn = Co \cdot P \cdot Cs \cdot 0.0047 \sum_1^{12} (ITr \cdot H - H) \quad (32)$$

Simplifying Eq. 32:

$$AECC = Co \cdot P \cdot Cs \cdot 0.0047 \sum_1^{12} H(ITr - 1) \quad (33)$$

where Co is the diesel fuel cost at the property (R$). All other variables have been already defined.

Determination of Additional Water Consumption Cost (AWCC). AWCC can be determined using Eq. 34.

$$AWCC = Q \cdot \sum_1^{12} (ITr \cdot H - H) \cdot Pa \quad (34)$$

Simplifying it becomes

$$AWCC = Q \cdot \sum_1^{12} H(ITr - 1) \cdot Pa \quad (35)$$

where Pa is the water price (R$ m^{-3}).

Additional Labor Cost (ALC). ALC can be determined by affecting Eq. 16 by ITr; and then by simplifying it becomes:

$$ALC = \sum_{irrigation_{days}=1}^{n} \left[\frac{S}{240}\right] \cdot \left[1 + \left(\frac{Holidays + T13 + INSS + IT}{100}\right) \cdot Hr \cdot (ITr - 1)\right] \quad (36)$$

These variables are defined at Eq. 16.

Yield Losses Cost (YLC). The costs due to yield losses can be calculated using Eq. 37.

$$YLC = YIKn - YIKv \quad (37)$$

where YIKn is the yield incomes obtained when the new sprayer kits are used(R$); and YIKv is the yield incomes obtained when the old sprayer kits are used (R$). It is defined as:

$$YIKv = \sum_i^n (Pc \cdot y_{UIA}) \quad (38)$$

where n is the number of crops harvest per year; Pc is the crop selling price (R$); and y_{UIA}: poorly irrigated area real crop yield (kg ha^{-1}), defined as:

$$y_{UIA} = (y_{dAIA} \cdot AIA) + (y_{dOIA} \cdot OIA) + (y_{dUIA} \cdot UIA) \quad (39)$$

where y_{dAIA} is the maximum possible crop yield for full water availability (kg ha^{-1}), defined as:

$$y_{dAIA} = y_m - \left(\frac{y_m \cdot K_y}{2b}\right)\left(X_{mAIA} - 2a + \frac{a^2}{X_{mAIA}}\right) \quad (40)$$

where ym, Ky, a and b were defined at Eq. 18; X_{mAIA} is the relative irrigation rate to reach maximum yield for AIA condition (decimals); AIA is the adequate irrigated area (ha). Defined by Montero et al. (1997) as the area that during a hydraulic evaluation has a water depth value collected between 0.85·MDC ≤ AIA ≤ 1.15·MDC. MDC is the mean depth collected and is defined by Eq. 41.

$$MDC = \frac{\sum_{i=1}^{n}(V_i \cdot S_i)}{S_i} \quad (41)$$

where Vi is the volume or depth of water collected in the collector "i" (ml or mm); Si is the distance between the collector "i" up to the point of pivot (m); Y_{dOIA} is the maximum possible crop yield on over irrigation (kg ha^{-1}); OIA is the over-irrigated area (ha), defined as the area that registered in a hydraulic evaluation a depth greater than 1.15·MDC; Y_{dUIA} is the maximum possible crop yield on a under-irrigated area (kg ha^{-1}); and UIA is the under-irrigated area (ha), defined as the area that registered, in a hydraulic evaluation, a depth less than 0.85·MDC.

According to Wu & Barragán (2000), to determine Xmi at Eq. 21, it is necessary to consider rainfall values or effective rain that may affect the volume delivered due to application efficiency (Ea), as:

$$X_{mAIA} = \frac{W_m}{MDC_{AIA} + Pr_{ef}} \quad (42)$$

where Wm is the water volume required to reach maximum yield (mm); MDC_{AIA} is the mean depth collected in the properly irrigated area (mm); and Pr_{ef} is the effective rain (mm).

To compute the yield at OIA zone, it would only be necessary to substitute in Eq. 18 the variable X_{mi} for X_{mOIA} (ratio between Wm to the sum of OIA and Pr_{ef}, in decimals). In a similar way, in Eq. 42, MDC_{AIA} would be substituted by MDC_{OIA} (mean collected depth on OIA). These substitutions are valid for the terms associated to the UIA conditions too.

The result would be:

$$y_{dOIA} = y_m - \left(\frac{y_m \cdot K_y}{2b}\right)\left(X_{mOIA} - 2a + \frac{a^2}{X_{mOIA}}\right) \quad (43)$$

$$X_{mOIA} = \frac{W_m}{MDC_{OIA} + Pr_{ef}} \quad (44)$$

$$y_{dUIA} = y_m - \left(\frac{y_m \cdot K_y}{2b}\right)\left(X_{mUIA} - 2a + \frac{a^2}{X_{mUIA}}\right) \quad (45)$$

$$X_{mUIA} = \frac{W_m}{MDC_{UIA} + Pr_{ef}} \tag{46}$$

Additional maintenance cost (AMC). The additional maintenance costs can be calculated using Eq. 47.

$$AMC = MCKv - MCKn \tag{47}$$

where MCKn and MCKv are the maintenance costs from the new and old sprayer kits, respectively (R$). Which are computed by Eq. 48 and 49.

$$MCKv = MCKn \cdot ITr \tag{48}$$

and,

$$MCKn = \sum_{i}^{n} MCTa \tag{49}$$

where n is the number of CPIM components; and MCTa is the annual maintenance cost (R$), defined as:

$$MCTa = \frac{Tm \cdot Vi}{100} \tag{50}$$

where Tm is the annual maintenance rate (%) (See Table 2); and Vi is the capital cost (R$).

For each system's component (n_i) the maximum life cycle value from Table 1 was taken. From here, a set of equations that relates annual maintenance rate and life cycle were determined (Table 2).

Table 2. Equations that relates maintenance time (Tm) and life cycle (T_{LC}) for center pivot irrigation machines components

Component of the watering system	Equation *
Fixed sprinkler	$Tm = T_{LC} - 1$
Centrifugal pump	$Tm = 0.22\ T_{LC} - 0.08$
Pumping Station (civil structures)	$Tm = 0.05\ T_{LC} - 7 \cdot 10^{-16}$
Diesel engine	$Tm = 0.3\ T_{LC} + 2$
Electric engine	$Tm = 0.2\ T_{LC} - 0.1$
Buried steel pipe	$Tm = 0.025\ T_{LC} - 3 \cdot 10^{-16}$
Pipe of superficial galvanized steel	$Tm = 0.1\ T_{LC} - 2 \cdot 10^{-15}$

*All the equations were obtained with a value of $r^2 = 1$

Substituting Eq. 46 in Eq. 47 and simplifying, then:

$$MCKn = \sum_{i}^{n} MCTa \cdot (ITr - 1) \tag{51}$$

The final expression when substituting Equations 29, 35, 36, 47 and 37 in Eq. 3 and simplifying for a CPIM with electric pumping station:

$$PMR + CIM \geq \left[(FDa_{TC} + FCa_{TC} + FDa_{TA} + FCa_{TA} + FDa_{TV} + FCa_{TV}) \cdot \frac{0.92}{\cos\varphi} \cdot (1 + ICMS) + Q \cdot \sum_1^{12} H \cdot Pa + \sum_{irrigation\_days}^{n} \left[\frac{S}{240} \right] \cdot \left[1 + \left(\frac{Holidays + T13 + INSS + IT}{100} \right) \cdot Hr \right] + \sum_i^n MCTa \right] \cdot (ITr - 1)[YIKn - (y_{dAIA} \cdot AIA) + (y_{dOIA} \cdot OIA) + (y_{dUIA} \cdot UIA)] \quad (52)$$

5 CONCLUSIONS

This paper proposed a theoretical mathematical model to define the best moment to renovate the pressure regulators and sprayers kits on a center pivot irrigation machine. This mathematical model is based on an analysis of operation and maintenance costs and diminishing agricultural yields in under irrigated areas, due to lack of uniformity along the irrigation line caused by worn pressure regulators and/or sprayers. This model allows the farmer to decide when is economically feasible to change emitters and pressure regulators to improve irrigation uniformity and making it economically profitable.

6 REFERENCES

ABO-GHOBAR, H. M. Losses from low-pressure center pivot irrigation systems in a desert climate as affected by nozzle height. **Agricultural Water Management**. V.21, p.23-32. 1992

ALLEN, R. G. Applicator selection along center pivots using soil infiltration parameters. Visions of the future. In: **NATIONAL IRRIGATION SYMPOSIUM**, 3., 1990, Phoenix, ASAE. p 549-555.

AL-KUFAISHI, S. A., Blackmore BS, Sourell H (2006) The feasibility of using variable rate water application under a central pivot irrigation system. **Irrigation Drainage Systems,** v.20, n. 2-3. p. 317-327,2006

ANDRADE, J. A. S.; et. al. Estratégias ótimas de irrigação para a cultura da melancia. **Pesquisa Agropecuária Brasileira**, Brunlia, v. 36, n. 2, p. 301-305, 2001.

BREMOND, B.; MOLLE, B. Characterization of rainfall under pivot: influence of measuring procedure. **Journal Irrigation and Drainage**, v. 121, n.5, p. 347-353, 1995.

BRENNAN, D. Factors affecting the economic benefits of sprinkler uniformity and their implications for irrigation water use. **Irrigation Science**, Acesso em: 13 Jun, 2007.

BORDOUSKY, J. P., et. al. Cotton Irrigation Management with LEPA systems. **Transations of ASAE**, v. 35, n. 3, p.879-884, 1992.

CHRISTIANSEN, J. Irrigation by sprinkling. **Calf. Agric. Exp. Stn**., B-670. Berkeley, p. 110-116, 1942.

ENGLISH, M. J.; Solomon, K. H.; Hoffman, G. J. A paradigm shift in irrigation management. **Journal Irrigation and Drainage**, v. 128, n. 5, p. 267-277, 2002

FACI, J. M.; et.al. Comparison of fixed and rotating spray plate sprinklers. **Journal Irrigation and Drainage**, v. 127, n. 4, p. 224-233, 2001

FRIZZONE, J. A.; et. al. Linear programming model to optimize the water resource use in irrigation projects: an application to the Senador Nilo Coelho Project. **Scientia Agrícola,** Piracicaba, v. 54, p. 136-148, 1997.

FRIZZONE, J. A. Função de produção. In. Faria, M. A.; et. Al. **Manejo da irrigação**. Lavras: UFLA/Sociedade Brasileira de Engenharia Agrícola, p. 86-116, 1998.

FRIZZONE, J. A**. Irrigación óptima**: perspectivas y desafíos. Dissertation (Full Professor) Departamento de Ingeniería Rural, ESALQ-USP, Piracicaba, 2003.

GILLEY, J. R., MIELKE, L. N. Conserving energy with low-pressure center pivot. **Journal Irrigation and Drainage**, p. 49-58, 1980.

HOFFMAN, G. J.; DERREL, L. M. Advanced Irrigation Engineering. International **Water Irrigation Review, v.** 14, n. 2, p. 24-29, 1994.

GORANTIVAR, S. D.; SMOUT, I. K. Allocation of scare water resources using deficit irrigation in rotational systems. **Journal Irrigation and Drainage**. v. 129, n. 3, p.155-163, 2003.

HERMANN, D. F.; HEIN, P. R. Performance characteristics of self-propelled center-pivot sprinkler irrigation system. **Trans ASAE** v. 11, n. 1, p. 11-15, 1968.

HEINEMANN, A. B.; et. al. Center pivot irrigation management optimization of dry beans in humid areas. **Trans. ASAE**. v. 43, n. 6, p. 1507-1516, 2000.

HEINEMANN, A. B.; Sousa, S. A. V.; Frizzone, J. A. Determinação da lâmina ótima de água para a cultura do milho doce na região de Sete Lagoas, MG. **Revista Brasileira de Engenharia Agrícola e Ambiental**. v. 5, n. 1, p. 147-151, 2001.

KELLER, J.; BLIESNER, R. D. **Sprinkle and tickle irrigation**. New York: AVI Book, 1990. Kincaid, D. C. Sprinkler pattern analysis for center pivot irrigation. **Irrigation Business and Technology** IV, v. 4, n. 4, p. 14-15, 1990.

KING, B. A., KINCAID, D. C. **Cooperative Extension System l**. Agricultural Experiment Station, University of Idaho. College of Agriculture, BUL, 797.

KLAR, A. E.; CASTRO, S. R. de; Duroha, C. Evaluation center pivot systems using new and old spray and pressure regulators. **IRRIGA**, Botucatu, v. 6, n. , p. 73-78, 2001.

LYLE, P.; BUTLER, G. Low energy labor from Texas pivot. **Irrigation Farmer,** v. 7, n. 4, p. 4, 1980.

MARQUES, P. A. A. **Modelo computacional para determinação do risco econômico em culturas irrigadas**. 2005. Dissertação (mestrado em agricultura) Escola superior de Agricultura "Luiz de Queirós", Universidade de São Paulo, Piracicaba, 2005.

MIRANDA, J. H.; PIRES, R. C. M. **Irrigação**, São Paulo: Sociedad Brasileira de Ingeniería Agrícola, 2003.

MONTERO, J.; et. al. Análisis de la distribución de agua en riegos con equipos pívot. In: **XV CONGRESO NACIONAL DE RIEGOS**, Lérida, p. 481-490, 1997.

MONTERO, M. J.; MARTÍNEZ, R. S.; TARJUELO, J. M. Analysis of water application cost with permanent set sprinkler irrigations systems. **Irrigation Science**, v. 23, p. 103-110, 2004.

OMARY, M.; SUMNER, H. Modeling water distribution for irrigation machine with small spray nozzles**. IRRIGA**, v. 127, n. 3, p. 156-160, 2001

PÉREZ, R.; et. al. Boquilla difusora cubana: criterios para el diseño hidráulico de los pivotes. **Revista Ciencias Técnicas Agropecuarias,** v. 10, n. 1, p. 79-83, 2001.

PÉREZ, R.; Alfonso, G. E. J.; Cárdenas, L. J. F.; López, C. G.; Alemán, G. C. Un estudio de la evaluación de la aplicación del riego en sistemas por pivote central. **Ingeniería Hidráulica en México**, v. 18, n. 3, p. 45-53, 2003.

PERRY, C. D.; Dukes, M. D.; Harrison, K. A. Effects of variable-rate sprinkler cycling on irrigation uniformity. An **ASAE/CSAE Meeting Presentation Paper**, n. 04, p. 11 - 17, 2004.

RIBEIRO, V. L. S. C. **Avaliação hidráulica de válvulas reguladoras de pressão novas e com diferentes tempos de utilização**. 2001. Dissertação (Mestrado em Irrigação e Drenagem), Universidade Federal de Ceará.

SOURELL, H. Desarrollo y uso del riego por goteo móvil. In: **Drip/Trickle Irrigation in Action**, Fresno, 1985. P. 597-602.

SOURELL, H. ; Faci, J. M. ; Playán, E. Performance of rotating spray plate sprinklers in indoor experiments. **IRRIGA,** Botucatu, v. 123, n. 5, p. 376-380, 2003.

SOUSA, S. A. V.; FRIZZONE, J. A.; Peres, F. C. Optimização da irrigação para diferentes déficits nas lâminas de água aplicadas às culturas. **Engenharia Rural**, v. 9, n. 1, p. 1-9, 1998.

TARJUELO, J. M. **El riego por aspersión y su tecnología**. 2. ed. Madrid: Editorial Mundi-Prensa, 1999.

WOOD, M.; WANG, Q. J.; BETHUNE, M. An economic analysis of conversion from border-check to centre pivot irrigation on dairy farms in the Murray Dairy Region, Australia. **Irrigation Science**, v. 26, p.9–20, 2007

WU, I. P.; BARRAGAN, J. Design criteria for microirrigation systems. **Transactions of the ASAE**, St. Joseph, v. 43, n. 5, p.1145-1154, 2000.

ZOCOLER, J. L. **Análise econômica de sistemas de irrigação**. In: Miranda JH, Pires RCM (ed) Irrigação, Jaboticabal, 2003. p. 653-703.