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MIRRIG: A decision support system for design and evaluation of microirrigation systems

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ARTICLE INFO

Article history:
Received 20 March 2008
Accepted 22 October 2008
Published on line 9 December 2008

Keywords:
Drip irrigation
Microsprinkling irrigation
Irrigation performance
Multicriteria analysis

ABSTRACT

The decision support system (DSS) MIRRIG has been developed to support the design of microirrigation systems and to advise farmers as a result of field evaluations. It is written in Visual Basic 6.0, runs in a Windows environment, and uses a database with information on emitters and pipes available in the market, as well as on crops, soils and the systems under design. MIRRIG is composed by design and simulation models and a multicriteria analysis model that ranks alternative design solutions based upon an integration of technical, economic and environmental criteria. User friendly windows are adopted for handling the databases and to manage the sub-models. The model allows creating and comparing a set of design alternatives relative to the pipe system and the emitters, either drip or microsprinkling emitters. For each alternative, the pipe system is sized and the irrigation system is simulated to produce performance, environmental and economic indicators. These include uniformity of water application, potential for contamination with agrochemicals due to water percolation, and installation and operation costs. Those indicators are used as attributes of the selected criteria. All alternatives are then compared and ranked through multicriteria analysis where the weights giving the relative importance of the adopted criteria are defined by the user. These procedures allow selecting the best design alternative and solving the complexities involved in the design of microirrigation systems. The model is available from the website www://ceer.isa.utl.pt/cms or by contacting cpedras@ualg.pt.

1. Introduction

Sustainable irrigated agriculture requires irrigation practices that are environmentally friendly, economically viable and lead to high irrigation performance (Wichelns and Oster, 2006; Oster and Wichelns, 2003; Pereira et al., 2002). Microirrigation systems have the potential for achieving high irrigation performance and offer a large degree of control, enabling accurate water and fertilizer applications according to crop-water and nutrients requirements, thereby minimizing environmental impacts and providing for increased performance and water productivity. Achieving this requires that systems are designed and operated in such a way that water is applied at a rate, duration and frequency that maximize water and nutrient uptake by the crop, while minimizing the leaching of nutrients and chemicals out of the root zone (Hanson et al., 2006). Highly uniform and timely water application is therefore required (Mermoud et al., 2005; Li et al., 2007) since the uniformity of nutrient distribution within a field depends

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0378-3774/$ – see front matter
doi:10.1016/j.agwat.2008.10.006

Nomenclature

a_p plant area (m^2)
a_w wetted area per plant (m^2)
A pipe section area (m^2)
A_p area of the field (ha)
AFC annual fixed cost (€ $year^{-1}$)
c^+, c^0, c^- concordance thresholds
C_{AB} concordance level
C_{en} energy pumping cost (€ $year^{-1}$)
C_{ma} maintenance labour cost (€ $year^{-1}$)
C_{op} labour cost to operate the irrigation system (€ $year^{-1}$)
C_v emitter coefficient of manufacturing variation
C_w water cost (€ $year^{-1}$)
D pipe diameter (m)
D_1, D_2 discordance thresholds
D_{AB} discordance level
EU emission uniformity (%)
f_i friction factor
f weak pair wise outranking relation
F strong pair wise outranking relation
g gravity acceleration ($m\ s^{-2}$)
$g_j(A)$ score of the alternative A according to the criterion j
G gross volume of water required per plant and per day ($L\ day^{-1}$)
h_{fT} total friction head loss in the lateral (m)
H pressure head (m)
H_a average emitter pressure head (m)
H_{CAB} computed pressure head at the upstream end of the system (m)
H_i pressure head at the emitter i (m)
H_L pressure head at the upstream end of the lateral (m)
H_m pressure head at the upstream end of the manifold (m)
H_n minimum pressure head at the emitters (m)
H_{REQ} pressure head required at the upstream end of the system (m)
H_x maximum pressure head at the emitters (m)
I_g gross irrigation requirement ($mm\ day^{-1}$)
I_n net irrigation requirement ($mm\ day^{-1}$)
IC_k initial cost or replacement cost of the component k (€)
K_e emitter discharge coefficient
L length of the pipe (m)
LR leaching requirement
n number of emitters
n_{comp} total number of components
n_{pa} period of the analysis (years)
n_{qe} number of emitters having flow rate rate $q_i > q_a$
n_{sub} total number of acquisitions of the component in the period
np number of emitters per plant
N_r number of irrigation events per year
N_{se} number of sectors of the irrigation system
OMC operation and maintenance cost (€ $year^{-1}$)
P_{aw} percentage area wetted (%)
P_D percentage of deficit relative to the required application depth (%)
P_{hs} localized head losses expressed as a fraction of the pipe head loss
P_j weight assigned to the criterion j
q emitter flow rate ($L\ h^{-1}$)
q_a average flow rate of the emitters ($L\ h^{-1}$)
q_d average flow rate of the emitters having $q_i < q_a$ ($L\ h^{-1}$)
q_i flow rate of the emitter i ($L\ h^{-1}$)
q_n minimum flow rate of the emitters ($L\ h^{-1}$)
q_x maximum flow rate of the emitters ($L\ h^{-1}$)
Q discharge ($L\ h^{-1}$)
Q_{CAB} computed upstream discharge ($L\ h^{-1}$)
Q_i discharge at the section i ($L\ h^{-1}$)
Q_L discharge at the upstream end of the lateral ($L\ h^{-1}$)
Q_m discharge at the upstream end of the manifold ($L\ h^{-1}$)
Q_{REQ} discharge required at the upstream end ($L\ h^{-1}$)
SC emitter's sensitivity to clogging
STV emitter's sensitivity to temperature variation
t_r irrigation application time ($min\ day^{-1}$)
T_{ac} annual interest rate
T_r peak-use-period transmission ratio
UC uniformity coefficient (%)
v_k lifetime of the component k (years)
V_p volume of water percolating out of the root zone ($mm\ year^{-1}$)
V_q emitter flow variation
VH pressure head variation
x emitter discharge exponent
Z_i elevation at the outlet i (m)
ΔEL difference in elevation between the up and downstream end of a pipe (m)
ΔH_{inc} pressure head computational increment (m)
ΔH_L allowed maximal variation of the pressure head in the laterals (m)
ΔH_m allowed maximal variation of the pressure head in the manifolds (m)
ΔH_{ml} allowed maximal variation of the pressure head in the mainline (m)
ΔH_s allowed maximal variation of pressure allowed in the sector (m)
ΔH_{sm} allowed maximal variation of the pressure head in the submain (m)

Greek symbols

Ω_F criteria set

upon the uniformity of water application, both of which affect crop yields (Santos, 1996; Hanson et al., 2006). If water is applied with low uniformity, some parts of the cropped field will receive more water and nutrients than others. Under-irrigation can reduce crop yields while over-irrigation will not result in increased crop yields, but will generate higher energy and fertilizer costs, and the loss of fertilizers and other chemicals leached with the percolating water.

The basic components of a microirrigation system are: the pump/filtration station, consisting of the pump, filtration equipment, controllers, main pressure regulators, control valves, water-measuring devices and chemical injection equipment; the delivery system, that includes the main and submain pipelines that transfer water from the source to the manifolds, which also may have filters, pressure regulators, and control valves; the manifolds, which supply water to the laterals and the laterals that carry water to the emitters (Pereira and Trout, 1999; Evans et al., 2007). Design of microirrigation systems is therefore complex considering the need to select and size all system components and the need to design for a targeted uniformity of water application (Bralts et al., 1987; Keller and Bliesner, 1990; Wu and Barragan, 2000). Uniformity is determined by a combination of design parameters, mainly referring to: the pressure at emitters and the variation in pressure along the unit or system, which depend upon the pipe sizing and related head losses; the pressure-discharge relation of the emitter, which refers to the sensitivity of the emitter to variations in pressure; the emitter characteristics relative to variations in discharge, mainly representing the sensitivity to clogging and to temperature; the coefficient of manufacturing variation for the emitter and the filtering capabilities of the system, which relates to the quality of irrigation water and the characteristics of the emitters (Pereira and Trout, 1999; Pereira et al., 2002).

Main advances in design of microirrigation systems refer to pipe sizing and layout and to the selection of emitters because these system components control the potential irrigation performance and costs. The design options relative to the pump, valves, controllers, filters and fertilizer devices are generally made after pipes and emitters are selected since they depend upon related pressure and discharges at the various nodes of the system network (Keller and Bliesner, 1990). However, their appropriate selection also influences the irrigation performance, and they also produce additional head losses that must be considered when sizing the system. To support and ease design, a variety of models have been developed such as for the pump/filtration station (Haghighi et al., 1989), for assessing emitter uniformity (Barragan et al., 2006), for pipe sizing (Kang and Nishiyama, 1996; Valiantzas, 1998, 2002; Demir et al., 2007) and for economic optimization of systems (Saad and Mariño, 2002; Valiantzas, 2003; Valiantzas et al., 2007).

Decision support systems (DSS) have started recently to be used in irrigation (Thysen and Detlefsen, 2006; Gonçalves et al., 2007; Smith et al., 2007). A DSS is a computerized system for helping any decision-making process, which integrates databases, modelling tools and multicriteria analysis methodologies that are useful to analyse and rank a set of alternatives. Supporting a decision means helping decision-makers to generate alternatives, rank them and make choices (Finlay, 1994), which is particularly useful for design. Supporting the selection-making process involves the estimation of the attributes relative to selected criteria for each alternative, evaluating them, comparing the alternatives, and to identify an ‘‘ideal’’ compromise between several and often adversative criteria. A DSS enables decision-makers to take into consideration complex and interacting factors. The main advantages from using a DSS are: an increased number of alternatives can be examined; better understanding of the business/processes; identification of unexpected situations; improved communication; cost savings; better decisions; time savings; better use of data and resources.

Multicriteria analysis (MCA) allows the integration of different kind of attributes and a trade-off analysis between technical, economic and environmental criteria. MCA facilitates the search for satisfactory compromises among adverse objectives that a designer needs to make. In irrigated agriculture, it is more often used for economic analysis (Bazzani, 2005; Riesgo and Gómez-Limón, 2006), water and land allocation (Latinopoulos, 2007), as well as for performance assessment, irrigation planning or water demand and delivery decisions (Rao et al., 2004; Raju et al., 2006; Oad et al., 2006). MCA applications to irrigation problems are often integrated in a DSS to be used together with simulation tools. This is the case of applications for the design of farm irrigation systems where solutions are aimed at satisfying requirements of technical, economic and environmental nature (Gonçalves et al., 2007; Gonçalves and Pereira, 2009).

This paper describes the underlying science and engineering of MIRRIG, a DSS developed for design of microirrigation systems and to support the evaluation of existing systems. MIRRIG is used to develop different design alternatives for the same field and to analyse and rank them based on technical, economic and environmental criteria using MCA. An application example including a sensitivity analysis of parameters used for ranking the alternatives is presented in a companion paper (Pedras and Pereira, 2008).

2. MIRRIG

MIRRIG was developed to design drip and microsprinkling systems, and as a tool to advise farmers about how to improve their microirrigation systems when using data obtained during field evaluation of systems under operation. It is written in Visual Basic 6.0 and runs in a Windows environment in a personal computer.

The conceptual structure of the model is presented in Fig. 1, where two main components are identified: the database and the models. The database contains information on emitters, pipes, crops, soils and the systems under design or under evaluation. The model's structure has 4 components: (1) a design module to iteratively size the pipe and emitters system for various design alternatives; (2) a performance analysis module that simulates the functioning of the system and computes the indicators used as attributes relative to the design criteria adopted for the multicriteria analysis; (3) the multicriteria analysis model ELECTRE II to rank the alternative design options; (4) an evaluation module that supports the analysis of data collected through field evaluations (ASAE, 1999) that can be used by designers and irrigation advisers when interactively working with farmers to evaluate possible improvements.

MIRRIG is mainly oriented to design and select the pipe system and emitters for an irrigation sector. It allows building up a variety of irrigation system's alternatives referring to both the pipe layout and the emitters. It does not support the

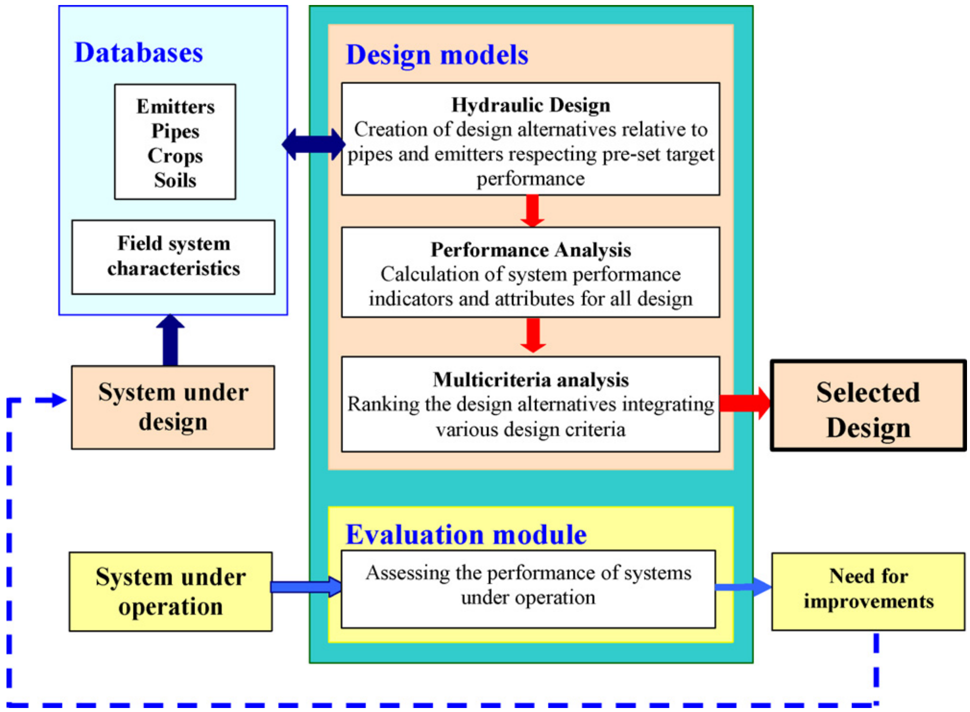

Fig. 1 – Conceptual design and evaluation structure of the DSS MIRRIG.

selection of filters but considers the respective pressure requirements when computing the system head losses. It also takes into account the pressure requirements of fertilizer units but not the respective design or selection. Relative to valves and controllers, the model considers localized head losses and the requirements for pressure controllers when the variation of pressure within a given pipe network is excessive. These requirements are expressed in terms of pressure and discharge at the nodes where equipment should be located. The pumping requirements are expressed in terms of upstream pressure and discharge.

The database MIRRIG.MDB concerns the emitters (drippers and microsprayers) and pipes available in the market, selected crops and soils, and fields/irrigation systems being designed. It was developed with Microsoft Access® and can be updated whenever required.

The emitters database contains information on emitters' characteristics as described by Keller and Bliesner (1990). Emitters are drippers or microsprayers; drippers may be on- and in-line emitters, including for subsurface drip irrigation. Emitters' characteristics include the nominal emitter flow rate and pressure head, the discharge-pressure relationship, the coefficient of manufacturing variation, the sensitivity to clogging (SC), the emitters' sensitivity to temperature variation (STV), the head loss coefficient of emitters insertion, price and lifetime. For microsprayers it includes the wetted radius and the wetted angle when they do not wet a full circle. The discharge-pressure relationship is

$$q = K_e H^x \tag{1}$$

where q is the emitter flow rate (L h^{-1}), H is the pressure head (m), K_e is the emitter discharge coefficient and x is the emitter discharge exponent; x is close to 0.5 for turbulent flow emitters and near 0 for pressure compensating emitters. When using drippers built in the pipe the database includes the pipe material, nominal pressure, internal and external diameters, and emitter spacing. The sensitivity to clogging is associated with the diameter of the emitter passageway and the possible emitter capability for flushing.

The pipe database refers to pipe material, internal and external diameters, nominal pressure, cost and lifetime. Data refers to pipes used for main lines, submains, manifolds and laterals.

The field/system database is created when the design is executed and stores data relative to all design alternatives created for that field. Each alternative contains the layout description of the mainline, submains, manifolds, laterals and emitters. Each system may be constituted by one or several sectors and subsectors depending upon the number of outlets of the main and submain pipes. This database includes data for identification of the system and sector being analysed, the field size, the soil, the crop, the crop layout rows (e.g. double or single lateral per plant row) and the pipe system layout. Crop irrigation requirements are computed externally, e.g. with the model ISAREG (Liu et al., 1998). Soil data refers to the saturated hydraulic conductivity, which is used to estimate the area wetted by each emitter using the equations proposed by Schwartzmass and Zur (1985) and Keller and Bliesner (1990). The area wetted by emitter may also be a user input when field observations are available.

Alternative pipe layouts refer to a variety of geometric configurations of pipe networks, with different lengths and slopes for the mainline, submains, manifolds and laterals, as

well as different locations for pressure regulators when these are required. Manifolds may be supplied through an end or the middle, and laterals may be located only at one side or both sides of the manifold. Alternatives on emitters refer to emitters of the same or different types, including on- and in-line drippers and/or microsprayers, as well as emitter spacings. The spacing between emitters is estimated from the respective wetted radius estimated as proposed by Schwartzmass and Zur (1985), or included in the emitters' database. The same information is used to select the spacing between laterals, the number of laterals per crop row in the case of tree crops, or to select between one lateral per crop row or two crop rows for field and horticultural crops. These data allow computing the number of emitters per plant and the percentage of area wetted. Each design alternative combines the selected options on pipe layouts and emitters. Table 1 summarizes the data requirements relative to one design alternative.

3. Pipe sizing

Research on microirrigation pipe sizing is abundant and includes finite elements (Saldivia et al., 1990; Bralts et al., 1993) and analytical approximations (Kang and Nishiyama, 1996; Valiantzas, 1998). Related advances allow the computation of the pairs pressure head–flow rate at each pipe outlet, thus easing design execution with respect to targeted uniformity performance.

In-line with these developments, pipe sizing in MIRRIG aims at finding the pipe diameters that best lead to achieve the user's performance targets relative to pressure variation within the operating system, i.e. that lead to the target uniformity of water application (considering selected locations for pressure regulation valves). Iterative computations are used to search for the best solution for each design alternative. The user selects the pipe characteristics from the database and inputs the design targets: the average pressure head for the selected emitter, H_a (m), the emission uniformity (EU, %) to be attained as set out in Table 2, and the allowable pressure head variation in the laterals, manifolds, submain and mainline.

The allowed maximal variation of the pressure head in the manifolds, ΔH_m (m) depends upon the allowed maximal variation of the pressure head in the laterals, ΔH_L (m), and the maximal variation of pressure allowed in the sector, ΔH_s (m). Following the methodology proposed by Keller and Bliesner (1990), it results

$$\Delta H_m = (\Delta H_s - \Delta H_L) \quad (2)$$

where ΔH_L is user defined and ΔH_s is given by

$$\Delta H_s = 2.5(H_a - H_n) \quad (3)$$

where H_a and H_n (m) are respectively the average and minimum pressure head at the emitters. The maximal variation of the pressure head allowed in the main and submain, respectively ΔH_{ml} (m) and ΔH_{sm} (m), are defined by the user.

Table 1 – Example of data characterizing the design alternative N_r 4.

Emitters	
Type	Dripper
Emitter constant, K_e	1.1851
Emitter discharge coefficient, x	0.4966
Coefficient of manufacturing variation, C_v	0.04
Pressure head, H (m)	10
Flow rate, q (L h^{-1})	3.4
Sensitivity to clogging, SC	1[a]
Emitter insertion head loss coefficient, K_{loc}	0.1
Price IC_k (€)	0.06
Lifetime (years)	15
Pipes	
Material	LDPE[b]
Pressure rating, laterals (kPa)	250
Pressure rating, manifold (kPa)	400
Laterals: inside diameter, D (mm)	14.8
Manifold: inside diameter, D (mm)	83
Price, laterals C_k (€/m)	0.1
Price, manifolds C_k (€/m)	2.1
Lifetime, υ_k (years)	15.0
Crops	
Crop	Citrus
Gross irrigation requirement (mm day^{-1})	6.0
Plant root depth (m)	1.0
Distance between plants in the row (m)	3
Major distance between plants rows (m)	5
Soils	
Type	Loamy-clay
Saturated hydraulic conductivity (mm h^{-1})	8.0
Irrigation system	
Number of sectors, N_{se}	2
Length of mainline (m)	14
Length of submain (m)	200
Supply to the manifolds	E[c]
Length of the manifolds (m)	125
Slope of the manifolds (%)	0.8
Laterals on 1 or 2 sides of manifold	2
Length of the laterals (m)	105
Slope of the lateral (%)	1.9
Option on laterals per plant row	3[d]
Pressure head at the system's upstream end (m)	15.0

[a] 1—very sensitive; 2—sensitive; 3—relatively insensitive.
[b] Polyvinyl chloride (PVC), low density and high density polyethylene (LDPE, HDPE).
[c] E—supply by one end and M—supply by the middle.
[d] Options: 1—one lateral per two plant rows, 2—one lateral per plant row and 3—two laterals per plant row.

Default restrictions are adopted relative to the maximum flow velocity in the pipes (2.5 m s^{-1}), the nominal pressure of the pipe in agreement with the selected pressure head H, and the admitted ratios between pipe diameters in successive sections.

The hydraulic computations follow the methodology proposed by Keller and Bliesner (1990) and Kang and Nishiyama (1996). They are performed iteratively, starting from downstream to upstream, i.e. starting at the laterals and ending at the mainline. An initial diameter is given to the lateral, which allows computing the pressure head H_L (m) and the discharge Q_L (L h^{-1}) at the upstream end of the lateral when knowing the average flow rate q_a and pressure head H_a

Table 2 – Indicators computed through the performance analysis simulation.

Indicators	Equations
Emission uniformity, EU (%)	$EU = 100\left[1.0 - \frac{1.27 C_v}{\sqrt{np}}\right]\frac{q_n}{q_a}$
Uniformity coefficient UC (%)	$UC = 100\left(1 - \frac{1}{n q_a}\sum_{i=1}^{n}\lvert q_i - q_a\rvert\right)$
Emitter flow variation, V_q	$V_q = \frac{q_x - q_n}{q_x}$
Pressure head variation, VH	$VH = \frac{H_x - H_n}{H_x}$
Relative application deficit (%)	$P_D = 100\left(1 - \frac{q_{qd}}{q_a}\right)$
Potential for contamination estimated by the volume of water percolating out of the root zone (mm year^{-1})	$V_p = \frac{N_{se}}{10 A_p}\left(\frac{t_r}{60}\right) N_r \sum_{j=1}^{n_{qe}}(q_i - q_a)$
Percentage area wetted, P_{aw} (%)	$P_{aw} = 100\left(\frac{a_w}{a_p}\right)$
Gross daily irrigation depth, (mm day^{-1})	$I_g = \frac{I_n}{(EU/100)(1-LR)} T_r$
Gross water volume per tree (L day^{-1})	$G = I_g\, a_p$
Irrigation application time (min day^{-1})	$t_r = \frac{G}{np\, q_a} * 60$
Annual fixed cost (€ year^{-1})	$AFC = \left[\frac{T_{ac}(1+T_{ac})^{n_{pa}}}{(1+T_{ac})^{n_{pa}} - 1}\right]\sum_{k=1}^{n_{comp}}\left(IC_k + \sum_{j=1}^{n_{sub}}\frac{IC_k}{(1+T_{ac})^{(j\times v_k)-v_k}}\right)$
Operation and maintenance cost, (€ year^{-1})	$OMC = C_{en} + C_w + C_{op} + C_{ma}$

All symbols are defined in the nomenclature box.

at the emitters, as well as the spacing and number of emitters in the lateral. H_L is computed as

$$H_L = H_a + 0.75\, h_{fT} + 0.5\, \Delta EL \quad (4)$$

where h_{fT} (m) is the total head loss in the lateral, and ΔEL (m) is the difference in elevation between the up- and downstream end of the lateral, positive when ascending, otherwise negative. The Darcy–Weisbach equation is used to calculate the head losses. Computations allow to identify the pairs pressure head–flow rate (H_i and q_i) at each emitter using the modified Kang and Nishiyama (1996) equation:

$$H_{i+1} = H_i + (Z_i - Z_{i+1}) - f_i \frac{1}{D}\frac{Q_i^2}{2 g A^2} L(1 + P_{hs}) \quad (5)$$

where H_i and H_{i+1} (m) are the pressure heads at the outlets i and $i+1$, Z_i and Z_{i+1} (m) are the elevations at the same locations, and the term on the right is the friction head loss for the pipe portion located between sections i and $i+1$ where the discharge is Q_i (L h^{-1}). In this term, f_i is the friction factor, g (m s^{-2}) is the standard acceleration of gravity, L is the length of the pipe (m) between the outlets i and $i+1$, D is the pipe diameter (m), A is the pipe section area (m^2), and P_{hs} is a factor to take into consideration the localized head losses as a fraction of the pipe friction head losses. P_{hs} is defined by the user.

These computations allow calculating the pressure head variation along the lateral and the flow velocity. These values are compared with those previously set: if target design conditions are not met, the model searches in the database for the lateral pipe of the same material with the next larger diameter, and the same computations are performed until conditions are met. The same computations are performed for all laterals and the minimum and maximum pressure heads at emitters, H_n (m) and H_x (m) are then identified. In case of laterals having built-in emitters, if the selected pipe does not fulfil the target design conditions, a message is displayed asking the user to select another diameter.

Similar iterative computations are performed for the manifold, the submains and the mainline until the pressure head variation meets the respective target conditions. The final pipe diameters are those that achieve the design targets. If this condition is not possible to be met, the user has to modify the design targets such as adopting a lower EU, increasing the upstream pressure head, modifying the system layout, selecting a different emitter, changing the allowed pressure head variations, and/or including pressure regulating valves in critical nodes of the system.

Results of pipe sizing of laterals, manifolds, submains and the mainline for every design alternative comprise the pipe lengths, diameters and respective material, discharges at the pipe's upstream end, mean flow velocity and pressure variation, as well as the discharge and pressure head required at the upstream end of the system, respectively Q_{REQ} and H_{REQ} (m). These results are used later for the performance analysis as described below.

4. Performance analysis

The performance analysis simulates the functioning of the irrigation system for all design alternatives, and computes a set of performance indicators characterizing each alternative, including those used as attributes relative to the adopted design criteria. The model computes the pressure head–flow rate couples for every pipe outlet of the network successively moving upstream from the furthest lateral located downstream on the manifold. Once these calculations are finished for the laterals, than the pressure head–flow rate couples are calculated for the manifold, then for the submain and finally for the mainline (Fig. 2). This process is also iterative until the computed pressure head H_{CAB} (m) at the upstream end of the system equals the pressure head H_{REQ} (m) required at the same location.

The simulation starts at the emitter located downstream in the lateral farthest from the inlet of the respective

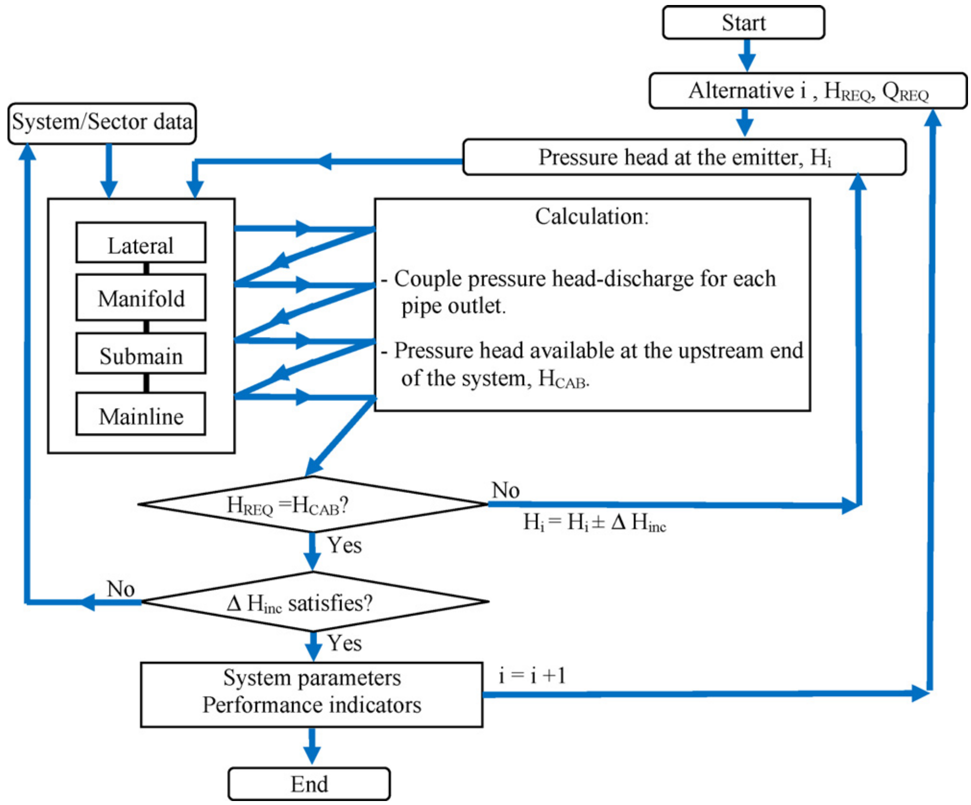

Fig. 2 – Schematic representation of the performance analysis procedure applied to any alternative i (H_{REQ} and Q_{REQ}: pressure head and discharge required at the upstream end of the system; H_{CAB}: computed upstream pressure head; H_i: pressure head at the last emitter; ΔH_{inc}: pressure head computational increment).

manifold. The pressure head $H_{i,o}$ (m) is assumed for that last emitter, to which corresponds the flow rate $q_{i,o}$, in agreement with the emitter equation (Eq. (1)). The pairs H_i and q_i are successively calculated for all emitters using Eq. (5). This calculation allows to compute the couple H_L–Q_L at the upstream end of the lateral. The simulation continues for all laterals supplied by the same manifold. In case the manifold supplies laterals on both sides, the procedure starts with the laterals at the left side and is repeated for the laterals on the right side in an iterative process until the pressure heads at the left and right side of the manifold are equalized. The couples H_i–q_i relative to every emitter of the sector supplied by the manifold, and the couples H_L and Q_L relative to the upstream end of the laterals supplied by that manifold become then known. Computations then follow in a similar way applying Eq. (5) successively to all outlets of the manifold to compute the respective pressure-discharge couples as well as the couple H_m–Q_m at the section where the manifold is supplied. Calculations are performed for all the manifolds and then to the submains and the mainline resulting in calculated pressure-discharge couples at all emitters, pipe outlets and nodes of the pipe system, including at the upstream end of the system, H_{CAB} (m) and Q_{CAB} (L h^{-1}).

H_{CAB} is compared with the required upstream pressure head H_{REQ}. If $H_{CAB} \neq H_{REQ}$ the iterative simulation restarts at the emitter located furthest downstream by adding to the initial $H_{i,o}$ value a pressure head computational increment ΔH_{inc}. The first ΔH_{inc} is ±2 m, positive or negative when H_{CAB} is under- or overestimated, which is halved in each successive iteration until it can be assumed that $H_{CAB} = H_{REQ}$, i.e. $|H_{CAB} - H_{REQ}| \leq 1 \times 10^{-7}$ m.

Table 3 – Results of the performance analysis relative to the design alternative N_r 4.

Indicators	Value
Area of a sector (ha)	1.3125
Number of emitters per sector	5250
Wetted area by an emitter (m^2)	0.84
Percentage of wetted area, P_{aw} (%)	33.7
Irrigation application time duration, t_r (min day^{-1})	256
Emission uniformity, EU (%)	93.9
Uniformity coefficient, UC (%)	97.3
Average flow rate of the emitters, q_a (L h^{-1})	3.5
Minimum flow rate of the emitters, q_n (L h^{-1})	3.3
Maximum flow rate of the emitters, q_x (L h^{-1})	3.8
Emitter flow variation, V_q (%)	13.3
Average pressure head of the emitters, H_a (m)	8.9
Minimum pressure head of the emitters, H_n (m)	7.9
Maximum pressure head of the emitters, H_x(m)	10.5
Emitter pressure head variation, VH (%)	24.9
Annual fixed cost, AFC (€ year^{-1})	396
Operation and maintenance cost, OMC (€ year^{-1})	323
Percentage of deficit relative to the required irrigation, P_D (%)	1.37
Volume of water percolating out of the root zone, V_p (mm year^{-1})	19.5

Table 4 – Objectives and attributes used for multicriteria analysis.

Objectives	Attributes
Minimizing costs	Annual fixed cost, AFC Operation and maintenance cost, OMC
Maximizing yields and incomes	Percentage of deficit relative to the required application, P_D
Minimizing environmental impacts	Percolated water volume indicating the potential to transport nitrates and agricultural chemicals out of the root zone, V_p
Maximizing hydraulic performances	Emission uniformity, EU Sensitivity to clogging, SC Sensitivity of emitters to temperature variation (STV)

At the end of the simulation, when the pressure head–discharge couples are known for all the emitters and outlets of the system, it is possible to compute a set of indicators and management parameters that characterize the design alternatives. These are defined in Table 2. The irrigation performance indicators (Wu et al., 1986; Keller and Bliesner, 1990; Pereira and Trout, 1999; Wu and Barragan, 2000) are the emission uniformity EU (%), the uniformity coefficient UC (%), the emitter flow variation, V_q, the pressure head variation, VH, the percentage of area wetted, P_{aw} (%), and the percentage of deficit relative to the required application P_D (%), which is used as indicator of the potential conditions of the system for achieving maximal yields and incomes.

The management parameters (Keller and Bliesner, 1990) include the gross daily irrigation depth, the gross volume of water required per tree and per day and the irrigation application time, t_r. Based upon these parameters, the model computes economic indicators (Avilez et al., 1987) including the annual fixed cost, AFC (€ year^{-1}) and the operation and maintenance cost, OMC (€ year^{-1}), and the percolated water volume V_p (mm year^{-1}), which is used as environmental indicator relative to the potential transport of nitrates and agrochemicals out of the root zone. An example of results characterizing an alternative is given in Table 3.

5. Multicriteria analysis

The design of an irrigation system is a multiobjective problem. Its solution implies that the decision-maker selects the best

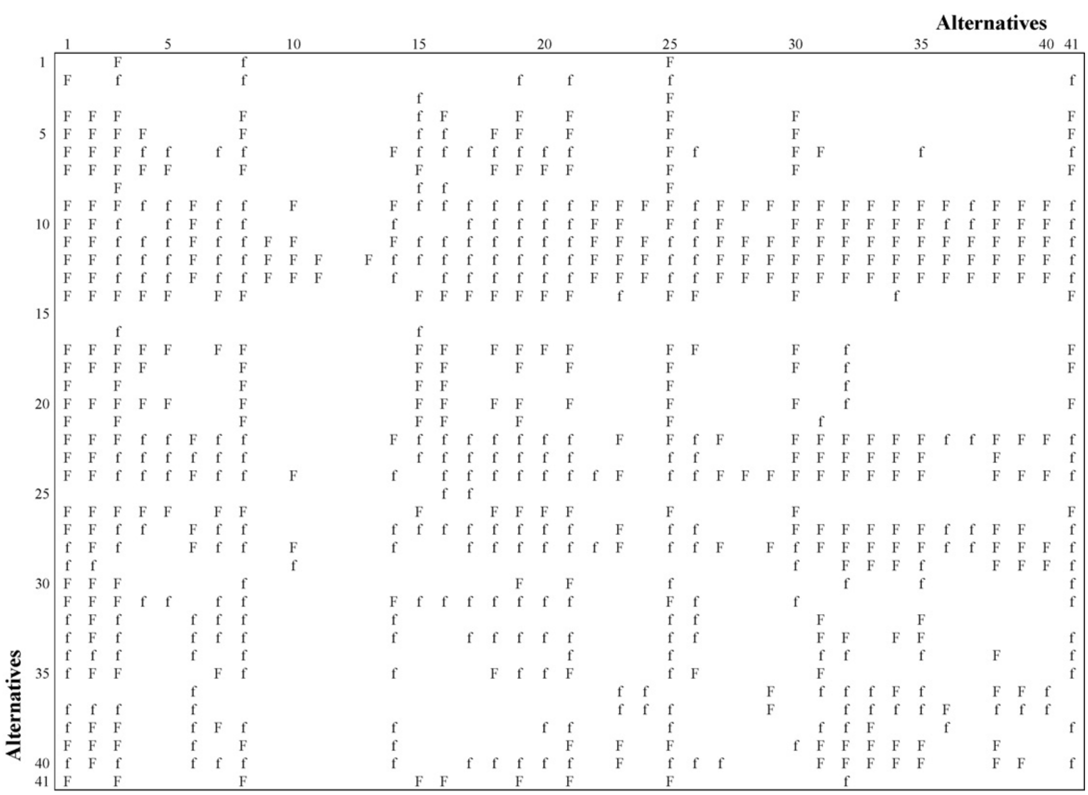

Fig. 3 – Matrix of outranking relations. Pixels with F and f refer to the cases where the alternative identified in Oy axis strongly or weakly dominates the alternatives identified in the Ox axis. Empty pixels indicate that the hypothesis of outranking between two alternatives is rejected; alternative 12 is dominating all other alternatives while alternative 15 is dominated by every other.

alternative based upon the attributes of all considered alternatives relative to the objectives to be achieved. Objectives are often adversative and a trade-off is required to select the best solution. MCA is applied to support the decision-making process of selection of the design alternative that better responds to the overall objectives.

A criterion is a quantitative or qualitative expression of a specific decision objective. Criteria are computed from attributes relative to the alternatives under consideration. The attributes are quantitative or qualitative measures of the degree to which a particular objective is attainable. A value or utility function is applied for deriving criteria values from the attributes. Thus, all alternatives have to be characterized by criteria attributes that allow their comparison and ranking using MCA (Vincke, 1992; Pomerol and Romero, 2000). Because the decision-maker does not recognize the same importance to all criteria, different weights are assigned to the criteria to express his preferences. In this application, the objectives are defined in Table 4 together with the indicators used to define the criteria attributes. These indicators are defined in Table 2. In addition, the emitters sensitivity to clogging and the emitters sensitivity to temperature variation are also used as attributes to characterize the selected emitters.

In MIRRIG, MCA follows the performance analysis. The outranking ELECTRE II method (Roy, 1996) is applied. It aims at ranking alternatives based on a pair wise comparison of alternatives and evaluates the degree to which scores in the criteria and their associated weights confirm or contradict the dominate pair wise relationships. Concordance and discordance concepts are used to rank the alternatives. The final ranking is found with resource of strong, F, and weak, f, outranking relations.

The concordance C_{AB} represents the degree in which the alternative A is better than the alternative B. The discordance D_{AB} reflects the degree to which the alternative A is worse than B for each criterion. They are defined as follows:

$$C_{AB} = \frac{1}{P} \sum_{j:g_j(A) \geq g_j(B)} P_j, \ldots \text{with}\, P = \sum_{j=1}^{m} P_j \quad (6)$$

$$D_{AB} = \begin{cases} 0\,\text{if}\, g_j(A) \geq g_j(B)\, \forall\, j \\ \max[g_j(B) - g_j(A)] \quad \text{if}\, g_j(A) < g_j(B),\, \forall\, j \in \Omega_F \end{cases} \quad (7)$$

where P_j is the weight assigned to the criterion j, $g_j(A)$ is the score of the alternative A according to the criterion j, and Ω_F is the criteria set as computed from the attributes characterizing the alternatives. The weights are $P_j > 0$ with $\Sigma P_j = 100$ and are selected by the user.

The outranking relations are calculated from the concordance thresholds ($c^+ \geq c^0 \geq c^-$) and discordance thresholds (D_1 and D_2) for each criterion, which are selected by the user. The strong F and weak f outranking relations are given respectively by

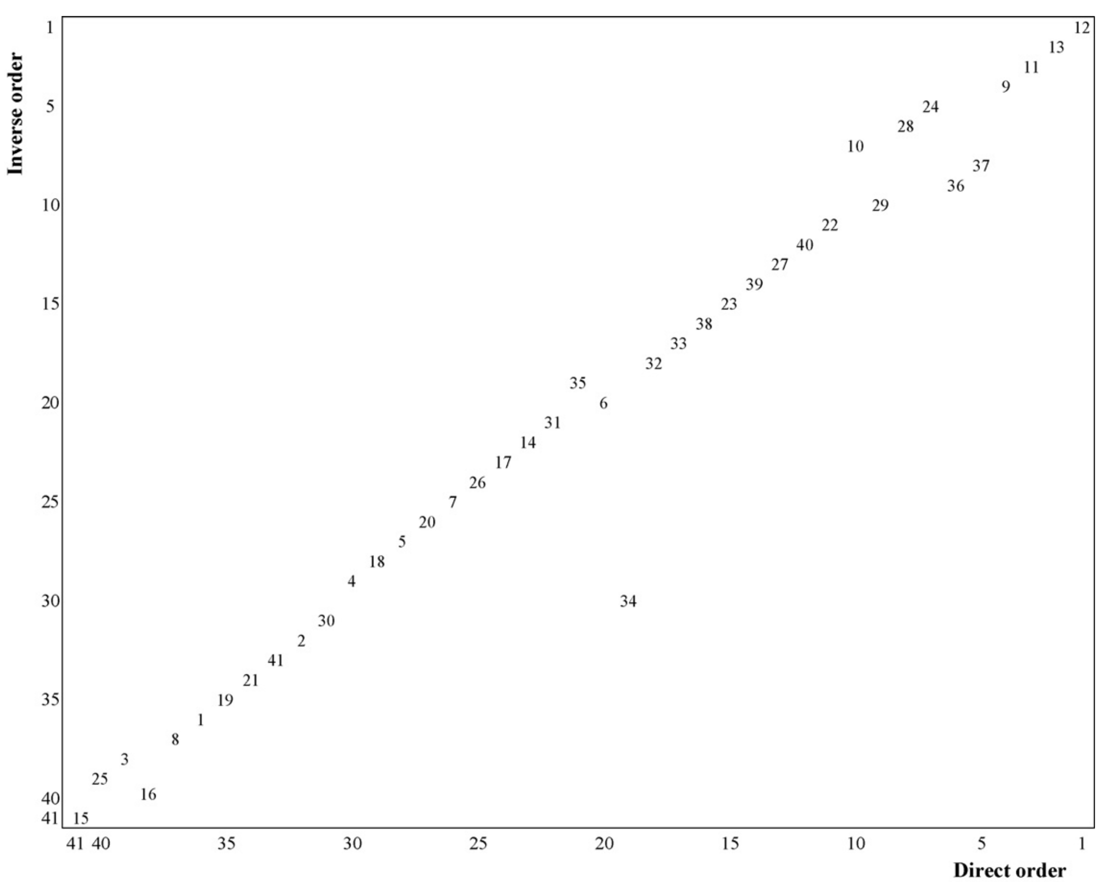

Fig. 4 – Ranking of alternatives (41) where the Ox axis refers to the direct ranking positions and the Oy axis refers to the inverse ranking position. The best alternatives are in the upper right corner and the worst in the lower left corner.

$$\left.\begin{array}{l} C_{AB} \geq c^{+} \\ g_j(B) - g_j(A) \leq D_{1(j)}\ \forall\ j \in \Omega_F \end{array}\right\} \text{and/or}$$
$$\left\{\begin{array}{l} C_{AB} \geq c^{0} \\ g_j(B) - g_j(A) \leq D_{2(j)}\ \forall\ j \in \Omega_F \end{array}\right. \tag{8a}$$

$$\left.\begin{array}{l} C_{AB} \geq c^{-} \\ g_j(B) - g_j(A) \leq D_{1(j)}\ \forall\ j \in \Omega_F \end{array}\right\} \tag{8b}$$

when the following relationship is valid:

$$\frac{\sum_{j:g_j(A) > g_j(B)} P_j}{\sum_{j:g_j(A) < g_j(B)} P_j} \geq 1 \tag{9}$$

The concordance thresholds (c^+, c^0, c^-) are defined in the range [0, 1]. An analysis of impacts of selected weights and thresholds on the MCA ranking is presented in a companion paper (Pedras and Pereira, 2008).

The MCA results may be shown in various ways. For a design case study of a microirrigation system for a citrus orchard in Algarve, southern Portugal, the comparison of 41 design alternatives through the matrix of outranking relations, F and *f* (Eq. (8a) and (8b)) is shown in Fig. 3. The empty pixels indicate that the hypothesis of outranking (or domination) between two alternatives is rejected. The alternative that shows the largest number of pixels with the symbols F and f is the best alternative. Contrarily, the alternative with the largest number of empty pixels is the worst.

The ranking of the same 41 alternatives is shown in Fig. 4. The Ox axis refers to the direct ranking position and the Oy axis refers to the inverse ranking position. ELECTRE II combines both rankings to result the ordering shown in the figure. The best alternative takes the upper right corner and the worst the bottom left one. When results are drawn for 2 or more alternatives they are shown in the same line. Alternatives that could not be compared would be situated in the right upper corner or in the left bottom corner. The analysis of results from both Figs. 3 and 4 allow the user to perform the selection of the best design alternative.

6. Conclusions

Microirrigation design is a multiobjective problem which decision-making requires the consideration of multiple criteria that may be supported by multicriteria analysis. The DSS MIRRIG has been developed with the objective of creating various design alternatives and then comparing and ranking them using MCA. The model provides the means to design, analyse, compare and rank numerous design alternatives taking into account the complex and interacting factors involved in the design of microirrigation systems and multiple objectives of technical, economic and environmental nature. Results show that the model is able to appropriately handle numerous design alternatives.

Because the attributes of design criteria are built from computed performance indicators and refer to economic and environmental aspects, MIRRIG is not only able to solve typical pipe sizing problems but also to deal with maximizing economic results and minimizing environmental impacts. Future improvements to MIRRIG will include linkages to an irrigation-scheduling model and to develop additional criteria relative to crop-water production functions. MIRRIG is available from the website www://ceer.isa.utl.pt/cms or by contacting cpedras@ualg.pt.

Acknowledgements

Field studies and its implementation in the south of Portugal were developed under the research project POCTI/AGG/42689/2001. The support of the Agricultural Engineering Research Center (Project POCTI-SFA-7-245) is also acknowledged. Thanks are due to Dr. Isabel L. Alves for carefully revising the manuscript.

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