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A Web-Based Decision Support System for Surface Irrigation Design

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1. Introduction

Surface irrigation systems have the largest share in irrigated agriculture all over the World. The performance of surface irrigation systems highly depends upon the design process, which is related to the appropriateness and precision of land leveling, field shape and dimensions, and inflow discharge. Moreover, the irrigation performance also depends on farmer operative decisions, mainly in relation to land leveling maintenance, timeliness and time duration of every irrigation event, and water supply uncertainties (Pereira, 1999; Pereira et al., 2002).

The design procedures of farm surface irrigation drastically changed in recent years. The classical ones based upon empirical rules (Criddle et al., 1956; Wilke & Smerdon, 1965). A quasi-rational methodology taking into consideration the main design factors was developed by the Soil Conservation Service and based upon intensive field observations (SCS, 1974, 1979). This methodology was widely applied and adopted with optimization procedures (Reddy & Clyma 1981a, 1981b). It assumes the soil classification in infiltration families related with soil texture and obtained from infiltrometer observations (Hart et al., 1980). For furrows design, an empirical advance curve was applied relating inflow discharge, slope, length, and infiltration. Other classical methods refer to the volume-balance models using the continuity equation and empirical information (Walker & Skogerboe, 1987; Yu & Sing, 1989, 1990; Clemmens, 2007). These type of models also apply to irrigation management (Latimer & Reddel, 1990; Camacho et al., 1997; Mailhol et al., 2005).

Numerous mathematical computer models for surface irrigation simulation were developed. They originated a new age of design methods, with increased quality of procedures because they allow the quantification of the integrated effect of main irrigation factors (length, discharge, slope, soil roughness, shape, and infiltration) on performance, thus, enlarging the solution set with higher precision and effectiveness than the traditionally empirical methods. Strelkoff & Katopodes (1977) first presented an application of zero-inertia modeling for border irrigation. Further developments were applied to borders, basins and furrows (Fangemeier & Strelkoff, 1978; Clemmens, 1979; Elliott et al., 1982), and were followed by furrow surge flow modeling (Oweis & Walker, 1990). The kinematics wave and the hydrodynamics model for furrows were later adopted (Walker & Humpherys, 1983; Strelkoff & Souza, 1984). Computer models for design of basin irrigation include BASCAD (Boonstra & Jurriens, 1978) and BASIN (Clemmens et al., 1993), and for border

irrigation include the BORDER model (Strelkoff et al., 1996). The models SRFR (Strelkoff, 1993) and SIRMOD (Walker, 1998) apply to furrows, basin and border irrigation and adopt various approaches for solving the continuity and momentum equations. Reviews were recently produced by Pereira et al. (2006) and Strelkoff & Clemmens (2007).

In addition to hydraulics simulation models, surface irrigation design requires the application of other type of models such as for irrigation scheduling, land leveling, distribution systems, and cost and environmental analysis. In practice, it is usually difficult to manage data for an interactive application of these models in design when they are not integrated with a common database. The decision support systems (DSS) methodology provides the framework to explore the synergy between mathematical simulation models, data and user knowledge through its integration aimed to help the decision-maker to solve complex problems. The DSS methodology makes handling data of various types easier and effective, and favors the integration of simulation models and their interactive application. It provides for a decision-maker learning process and it supports a decision process and related choices through multicriteria analysis. DSS models are often applied to irrigation planning and policy analysis (Bazzani, 2005; Riesgo & Gómez-Limón, 2006), as well as to performance assessment and water demand and delivery simulation (Raju & Duckstein, 2002; Rao et al., 2004; Oad et al., 2006; Raju et al., 2006). However, few applications are developed for irrigation design (McClymont, 1999; Hornbuckle et al., 2005; Gonçalves et al., 2009; Pedras et al., 2009).

The variety of aspects influencing irrigation performance (Burt et al., 1997; Pereira and Trout, 1999; Pereira et al., 2002) makes the design process quite complex, and a multicriteria analysis approach is then advantageous. Alternative design solutions may be ranked following various objectives and criteria, such as improving the irrigation performance, achieving water saving, attaining high water productivity, or maximizing farm incomes. Using a DSS and multicriteria analysis is helpful to produce appropriate comparisons among alternative design solutions and to perform a trade-off analysis (Roy & Bouyssou, 1993; Pomerol & Romero, 2000). In this line, the DSS SADREG for surface irrigation design was developed, tested and applied to different agricultural, economical and environmental conditions, considering several irrigation methods, equipments and practices. Applications include the Lower Mondego Valley, Portugal, improving basin irrigation for water savings and salinization control in the Upper Yellow River Basin, China, improving furrow irrigation in Fergana Valley, Aral Sea Basin, Uzbekistan, and modernizing furrows and border irrigation in Euphrates Basin, Syria. The objective of this chapter is to present the DSS model and its Web application, describing procedures to design and users support.

The development of DSS for Web allows a better application flexibility, improving the user support for database access, and enlarging the number of users, particularly in the world areas where the water scarcity demand for a better use of irrigation water. The application version here presented comprises a Web and a simulation engine module, which includes the models integrated in SADREG. The Web access of DSS allows an easier transfer of knowledge and tools to improve the procedures to evaluate and design field irrigation systems. The DSS location on a server allows data sharing and comparison of results by different users. Some examples of Web applications in the irrigation domain show its usefulness (Thysen and Detlefsen, 2006; Car et al., 2007).

The organization of this chapter considers, first, the description of DSS model, with details about the process of design and selection of surface irrigation alternative; after, in sub-chapter 3, the explanation of Web methodologies in a DSS context, referring the

programming languages and the architecture of Web client and server; and, in sub-chapter 4, the description of the DSS software use and Web interface.

2. DSS model

SADREG is a DSS designed to assist designers and managers in the process of design and planning improvements in farm surface irrigation systems – furrow, basin and border irrigation. It includes a database, simulation models, user-friendly interfaces and multicriteria analysis models.

2.1 DSS architecture

SADREG is comprised of two components: design and selection (Fig. 1). The first component applies database information and produces a set of design alternatives in agreement with the user options. These alternatives are characterized by various hydraulic, economic, and environmental indicators that allow appropriate selection and ranking. The selection component is based upon multicriteria analysis for ranking the alternatives, thus, supporting the decision-maker to select the best design solution. The decision-maker participates in all decision processes through interface dialogue structures that allow expressing design and management options and priorities.
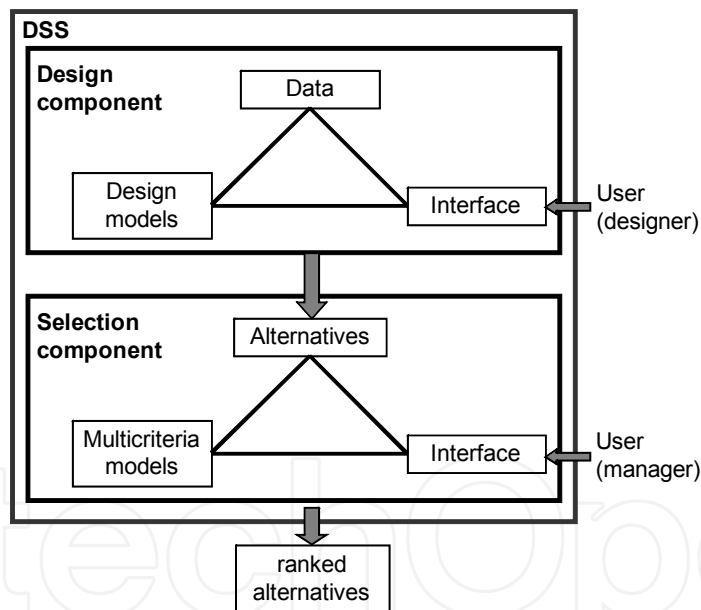

Fig. 1. Conceptual structure of SADREG

The database refers to data of various natures, some constituting input data required for computations, others are created through successive computations (Fig. 2). Main components are:

1. General field data, relative to soils and environment (e.g., soil infiltration, soil water holding capacity, soil salinity, groundwater depth, and climate), crops (planting date, yields, yield function parameters), equipment characteristics and costs, and operational costs and benefits;
2. Field data characterizing the field under design: length, width, slopes, surveying data, and characteristics of the respective water supply;

3.   Data created through simulations performed with the models SIRMOD for surface irrigation simulation (Walker, 1998) and ISAREG for irrigation scheduling simulation (Pereira et al., 2003);
4.   Projects data, referring to data characterizing the design alternatives; and
5.   Selection data, referring to the value functions and decision priorities.

Fig. 2. Data base components in relation with respective data sources and uses in the design process

SADREG includes various computational models and tools (Fig. 3). The simulation of the surface irrigation systems – furrows, borders, and basins – is performed by the surface irrigation simulation model SIRMOD (Walker, 1998), which is integrated within SADREG. The water balance simulation to define the application depths and timings is performed by the ISAREG model (Pereira et al., 2003), which is linked (loose integration) with SADREG and explored interactively. Calculations relative to land leveling and farm water distribution systems are performed through specific built-in tools. These computational tools provide for the characterization of each design alternative, including a complete set of performance indicators. The resulting data are later handled by an impact analysis tool, so creating all data required for multicriteria analysis. The impact analysis tool performs calculations relative to crop yields and related incomes (benefits), costs, and environmental impacts as described later. Ranking and selection of alternatives are performed with composite programming and the ELECTRE II models (Roy & Bouyssou, 1993; Pomerol & Romero, 2000).

The SADREG applications scope comprises: (a) a single field analysis relative to alternative design options for furrow, basin, or border irrigation, considering several decision variables such as field slopes, farm water distribution systems and runoff reuse; and (b) an irrigation

sector analysis, when a spatially distributed database relative to the farm systems is available. In this case, the alternatives are assessed jointly with modernization options relative to the conveyance and distribution network. It applies to farm land parcels or fields, of rectangular shape, with a well known geographical location, supplied by a hydrant, a gate, or other facility at its upstream end.
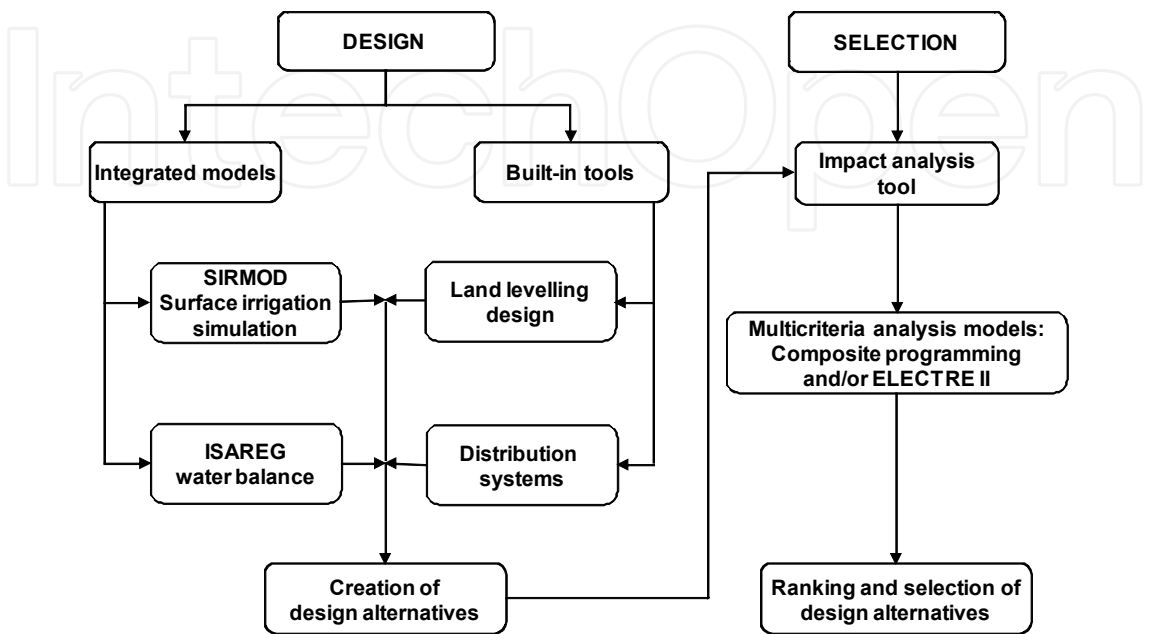

Fig. 3. Model base components

A field is characterized by its length and width, slope and land surface unevenness, soil infiltration and soil water retention characteristics, both assumed as spatially uniform for design purposes. Large fields may be subdivided into units, which are field fractions supplied by a single outlet, all having the same width, length, and slope. In addition, subunits may be considered when the water available or management constraints impose that a unit is not fully irrigated simultaneously. In order to design the upstream water distribution, the field characterization requires definition on which direction, OX or OY, the distribution system should be located. Hydrants or farm gates supply the water to the field with known discharge and hydraulic head. In large fields, farm canals or pipes supplied by those hydrants or gates may deliver the water to the upstream distribution system through various outlets, equaling the number of units. In small fields, generally only one unit is considered and the outlet coincides with the hydrant or gate.

A hierarchical approach is used to develop the design alternatives (Fig. 4). Data referring to field characteristics common to all alternatives are organized in a *workspace*. Included in the field workspace are the *projects* whose data structure is aimed at developing a set of design alternatives relative to:

1. The crop type (e.g., cereals versus row crops),
2. The irrigation method;
3. The land leveling solution, to be defined in agreement with the irrigation method, field longitudinal and cross slopes, and the selected upstream distribution side,
4. The water supply conditions that influence, together with the irrigation method, the options relative to the number and size of units and the outlet's discharge; and
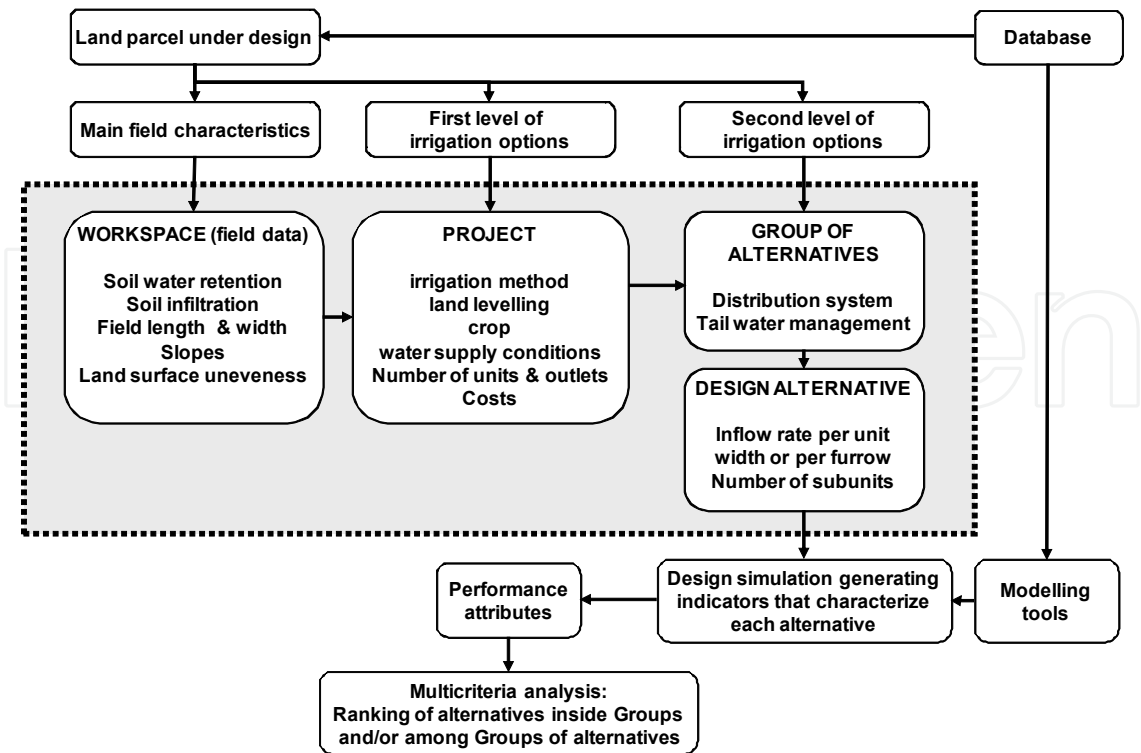5. Costs and other financial parameters.

Fig. 4. Scheme of the creation of field design alternatives using a multilevel approach for design and application of multicriteria ranking and selection

The design alternatives are clustered into *groups* included in a project and relative to:
1. The upstream distribution system, which depends upon the selected irrigation method and equipment available; and
2. The tail end management system, which also depends upon the irrigation method and the equipment available.

The *alternatives* constitute complete design solutions. Within a group, they are differentiated by the operative parameters: the inflow rate per unit width of land being irrigated or per furrow, and the number of subunits.

2.2 Irrigation system design
2.2.1 Decision variables
The surface irrigation methods considered are level basin irrigation, with flat or furrowed soil surface, graded basins, borders, and graded furrows (Table 1). Level furrows are treated as furrowed level basins. For cereals, furrows of corrugated type may be considered.

The decision variables relative to the irrigation design process are described in Table 2. They depend upon the irrigation method since it influences the field layout and land leveling, the water supply and distribution, the tail water management, and the farm irrigation management.

2.2.2 Land leveling
When starting a project, the user must select the irrigation method, the upstream distribution side, and carry out a land leveling simulation adopting cross and longitudinal field slopes appropriate to the considered irrigation method and the actual field slopes. The land leveling simulation tool computes the cut and fill volumes required to change from the actual elevations $z_a(x, y)$ into the target elevations:

$$z(x,y) = z_0 + S_x(x-x_0) + S_y(y-y_0) \qquad (1)$$

where x_0, y_0, z_0 = coordinates of the centre of gravity of the field (m); and S_x and S_y = longitudinal and cross slopes (m m^{-1}) along the OX and OY axis, respectively (Dedrick et al., 2007). The plan position (value of z_0) is iteratively changed until the cut to fill ratio becomes > 1.0 and < 1.2 (Fig. 5). Results include the cut and fill depths and volumes, and related costs.

Irrigation method	Soil surface condition	Field slopes	Field inflow conditions	Tail end conditions
Level basin	Flat or furrowed	Zero in all directions	Point inflow at one or various locations, or to individual furrows	Diked
Graded basin and borders	Flat or furrowed	Longitudinal slope ≠ 0 and cross slope = 0	Point inflow at one or various locations, or to individual furrows	Diked for basins and open for borders
Graded furrows	Furrowed	Longitudinal and cross slope ≠ 0	Inflow to individual furrows	Open or diked

Table 1. Irrigation methods

2.2.3 Infiltration and SIRMOD application

The modified Kostiakov equation is applied in SIRMOD model (Walker, 1998) to compute soil infiltration. For continuous flow, it takes the form:
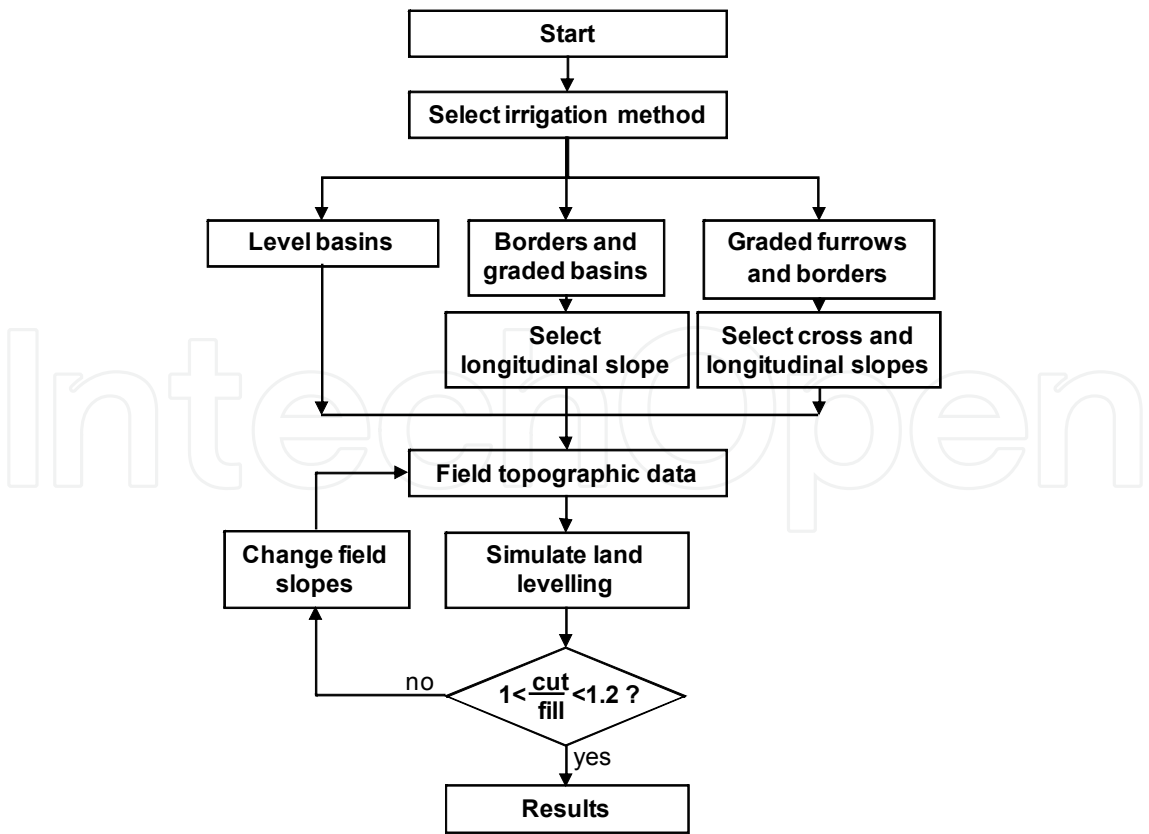
Fig. 5. Flowchart of the application of the land leveling simulation tool.

$$Z = K \cdot \tau^a + f_0 \cdot \tau \qquad (2)$$

where Z = cumulative infiltration (m³ m⁻¹); τ = infiltration time (min), K (m³ m⁻¹ min⁻ᵃ) and a (dimensionless) are empirically adjusted parameters; and f_0 = basic infiltration rate (m³ min⁻¹ m⁻¹).

For surge-flow, the procedure developed by Walker & Humpherys (1983) is adopted:

- For infiltration on dry soil (first wetting), Eq. (2) is applied;
- For infiltration on wetted soil (third and successive wettings) the parameters a, K and f_0 in Eq. (2) are modified into K_s, a_s, and f_{0s}, thus, producing the surge infiltration equation; and
- For infiltration during the second wetting, a transition curve is applied.

This transition equation balances the effects represented by the equations for dry and wetted soil (Walker, 1998; Horst et al., 2007):

$$Z = [K + (K - K_s)\, FP]\,^{\tau[a + (a - a_s)\, FP]} + [f_0 + (f_0 - f_{0s})\, FP]\, \tau \qquad (3)$$

where FP (dimensionless) = distance-based factor computed from the advance distances x_{i-2} and x_{i-1} relative to the surge cycles $i-2$ and $i-1$.

To characterize each field, SADREG includes a set of infiltration data concerning families of infiltration curves for continuous and surge flow, typical of seasonal irrigation events (first, second, and later irrigations) under flat soil infiltration conditions. Field observations of infiltration can be added to this set of infiltration curves and be used for the respective design case study. When no field infiltration data are available, the user selects the curves to be used considering the available soil data. To adjust the parameters for furrow irrigation, the procedure proposed by SCS (1979) and Walker (1989) is applied. It is based on the average wetted perimeter WP (m) and the adjusting coefficient (C_{adj}). WP is given by

$$WP = 0.265 \left(\frac{q \cdot n}{\sqrt{S_0}} \right)^{0.425} + 0.227 \qquad (4)$$

where q = furrow inflow discharge (l s⁻¹); n = Manning's roughness coefficient (s m⁻¹ᐟ³); and S_o = furrow longitudinal slope (m m⁻¹). The adjusting coefficient C_{adj} is estimated as

$$C_{adj} = 0.5,\ldots if\ \frac{WP}{FS} < 0.5 \text{ , else } C_{adj} = \frac{WP}{FS} \qquad (5)$$

where FS (m) = furrow spacing. The parameters K and f_0 [Eq. (2)] and the surge-flow infiltration parameters are adjusted as

$$K_{adj} = C_{adj} \cdot K \qquad (6)$$

$$f_{0\ adj} = C_{adj} \cdot f_0 \qquad (7)$$

SIRMOD model is applied for several input conditions that cover all situations relative to the user options to create alternatives. The continuous input variables consist of: field length

Decision variables		
Design	Field layout and land levelling	- upstream distribution side (OX or OY)
		- field length (FL) and field width (FW)
		- cross slope (S_{oC})
		- longitudinal slope (S_o)
	Water supply conditions	- number of outlets (N_o)
		- number of units (N_u)
		- total field supply discharge (Q_F)
		- outlet discharge (Q_o) and hydraulic head (H_o)
		- time duration of field delivery (t_F)
	Farm distribution system	- continuous and constant inflow rate for basins and borders
		- continuous or surge flow with automatic or manual surge valves for graded furrows,
		- lined or unlined canal, or gated pipes, or layflat tubing (for all methods)
	Tail water management	- no tail water runoff (case of basins and diked furrows)
		- open tail end without tail water reuse
		- open tail end with reuse by pumping to the upstream end
		- open tail end with gravity reuse on downstream fields
Management	Irrigation scheduling	- irrigation timing
		- required application depths
		- application time duration (t_{ap})
	Distribution system operation	- inflow rate per unit width or per furrow (q_o)
		- number of sub-units (n_s)

Table 2. Design and management decision variables

(*FL*, m), required application depth (Z_{req}, mm), field longitudinal slope (S_o), Manning's hydraulics roughness coefficient (*n*), furrow spacing (*FS*), and inflow rate per unit width or per furrow (*q*, l s^{-1}). The discrete input variables required are: inflow regime (continuous or surge flow), tail end management (diked, open, or open with reuse), cross section shape (flat or a given furrow type), and parameters of the infiltration equation.

Any run of SIRMOD produces output data including: application, advance and recession times; infiltration depths; runoff and percolation volumes; and performance indicators, mainly those defined in Table 3 (Walker & Skogerboe 1987; Pereira & Trout 1999).

Indicator	Definition	Units
Application efficiency	$E_a = \begin{cases} \dfrac{Z_{req}}{D} \times 100 & Z_{lq} > Z_{req} \\[2mm] \dfrac{Z_{lq}}{D} \times 100 & Z_{lq} < Z_{req} \end{cases}$	%
Distribution uniformity	$DU = \dfrac{Z_{lq}}{Z_{avg}} \times 100$	%
Water requirement efficiency	$E_r = \dfrac{Z_{avg\,(root)}}{Z_{req}} \times 100$	%
Infiltration efficiency	$IE = \dfrac{Z_{avg}}{D} \times 100$	%
Tail water runoff ratio	$TWR = \dfrac{Z_{run}}{D} \times 100$	%
Deep percolation ratio	$DPR = \dfrac{Z_{dp}}{D} \times 100$	%

Z_{req} - the average water depth (mm) required to refill the root zone in the lower quarter of the field
D - the average water depth applied to the irrigated area (mm)
Z_{lq} - the average depth of water infiltrated in the lower quarter of the field (mm)
Z_{avg} - the average depth of water infiltrated in the whole irrigated area (mm)

$Z_{avg\,(root)}$ - the average depth of water infiltrated stored in the root zone (mm)
Z_{run} - the depth of water that runs off at the tail end of the field (mm)
Z_{dp} - the depth of water that percolates below the root zone (mm)

Table 3. Performance indicators

SIRMOD is used iteratively for a given alternative to search the irrigation parameters referred to above that comply with the application of the required irrigation water depth Z_{req} (mm). This one is computed by running interactively the model ISAREG for the considered crop, soil, and climate. In SIRMOD simulation, an appropriate inflow rate q (q_{min} $< q < q_{max}$, $l\,s^{-1}\,m^{-1}$) is iteratively selected using increments $\Delta q = 0.1\ l\,s^{-1}$. However, it may happen that the model does not converge and it becomes necessary to have a successful simulation trying different combinations of internal simulation parameters (Walker, 1998): time step (1-2.5 minutes), space step (1-25 m, according to the field length), time weight factor (0.60-0.65), space weight factor (0.50-0.65), and type of hydraulics simulation model (full hydrodynamic or zero inertia). When an inflow rate q is found a new iteration starts to compute the time t_{ap} (min) required to apply the water depth Z_{req}. This is performed by maximizing the water requirement efficiency (Table 3), which should become close to 100%.

Results are then saved in the database to be further applied to other alternatives. The results for intermediate values for each of the continuous input variables are calculated by interpolation between those stored in the database instead of running the model several times.

2.2.4 Generation of alternatives

The procedure to build up and characterize design alternatives for a given field is performed through the following sequential steps:

1. Selection of the irrigation method: level basin (flat or furrowed), graded basins or border, or graded furrows; for furrows, selection includes the cross section type and the furrow spacing;

2. Definition of the field side, along the axis OX or OY, where the upstream distribution facilities will be located;

3. Land leveling simulation, with selection of the field slopes more appropriate to the irrigation method, and the actual field topography;

4. Selection of the inflow regime for graded furrows: continuous or surge-flow. The surge-flow irrigation management follows the one-fourth length rule for the advance phase, i.e., with increased duration of successive cycles; after the advance is completed, a continuous flow with half-inflow rate applied to the full unit is adopted. For basin and borders, only a continuous inflow rate is considered;

5. Definition of the number of outlets and field units;

6. Selection of the water distribution system: gated pipe, lay-flat tubing, earth canal, or lined canal; when the surge-flow option is selected, the respective control system may be either manual or automatically operated;

7. Selection of a tail water management option for borders and furrows: diked, i.e., closed at the tail end, or open. When open, the tail end runoff may be reused by pumping to the upstream end, reused by gravity in downstream fields, or not reused. Basins are diked; and

8. Estimation of an appropriate crop irrigation scheduling, thus, the required application depths and timings. With this purpose, the ISAREG model is used interactively with SIRMOD for searching the application depths appropriate to the irrigation method.

2.2.5 Impact evaluation

The cost analysis considers the investment and the operation and maintenance (O&M) costs (Mjeld et al., 1990; Solomon et al., 2007). The investment cost refers to the farm distribution system equipment and the initial land leveling. The net present value of the investment cost is calculated on a yearly basis using a capital recovery factor that is a function of the annual interest rate and the lifetime of the components (Tab. 4). The annual O&M costs include land leveling maintenance, distribution system operation and maintenance, and reuse pumping costs. The database shall include the duration times relative to all irrigation tasks depending upon the irrigation method and the equipment used. The production costs not referring to irrigation (e.g. fertilization, cultivation, and harvesting) do not differ among alternatives and do not interfere on ranking and selection of alternatives. Thus, they are not included in the cost analysis.

Investment costs (IC):	Formulas
IC$_{va}$ - Present worth cost of one given component (€)	$IC_{va} = IC \cdot \left(1 + \left[\sum_{j=1}^{N_{sub}} \left(\frac{1}{1+i_{TA}} \right)^{j \cdot N_{LT}} \right] \right)$
CRF - capital recovery factor (-)	$CRF = \dfrac{i_{TA} \cdot (1+i_{TA})^{N_{AP}}}{(1+i_{TA})^{N_{AP}} - 1}$
AFC - Annual fixed cost (€/year)	$AFC = CRF \cdot \sum_{j=1}^{N_{comp}} IC_{va_j}$
IC$_{LL}$ - initial land leveling cost (€)	$IC_{LL} = a_0 + a_1 \cdot t_{mac}$
t$_{mac}$ - time machine operation for land leveling (h)	$t_{mac} = t_{uexc} \cdot V_{exc}$ or $t_{mac} = t_{uarea} \cdot A$
IC$_D$ - distribution system cost (€)	$IC_D = b_0 + b_1 \cdot FW$
IC$_R$ - reuse system cost (€)	$IC_R = r_0 + r_1 \cdot A$
IC$_T$ - total investment annual cost (€/year)	$IC_T = IC_{LL} + IC_D + IC_R$
OMC - Operation & maintenance costs:	
OMC$_R$ - Reuse pumping system cost (€/year)	$OMC_R = r_2 \cdot VR$
OMC$_{LL}$ - Land leveling maintenance cost (€/year)	$OMC_{LL} = a_0 + a_1 \cdot a_2 \cdot A$
OMC$_D$ - Distribution system cost (€/year)	$OMC_D = h_0 \cdot t_{Mt}$
t$_{Minst}$ - labour to install the distribution system (h/year)	$t_{Minst} = h_1 \cdot FW$
t$_{Mrem}$ - labour to remove the distribution system (h/year)	$t_{Mrem} = h_2 \cdot FW$
t$_{Mope}$ – labour to operate a sub-unit (h)	$t_{Mope} = h_3 \cdot S_U W$
t$_{Mfree}$ - free man power time in a sub-unit irrigation (min)	$t_{Mfree} = t_{ap} - t_{Mope}$
t$_{MopU}$ - total labour to operate a unit (h)	$t_{MopU} = t_{MopSU} \cdot ns, \ldots \text{if } t_{Mfree} > t_{Mm}$ $t_{MopU} = t_{ap} \cdot ns, \ldots \text{if } t_{Mfree} \leq t_{Mmin}$
t$_{Mt}$ - total labour by the distribution system (h/year)	$t_{Mt} = t_{Minst} + \sum_{j=1}^{Nirrig} (N_u \times t_{MopU})$
OMC$_T$ – total O&M annual cost (€/year)	$OMC_T = OMC_{LL} + OMC_D + OMC$
Symbols: *A=field area (ha)* *a$_0$* =leveling machines fixed cost (€/operation) *a$_1$* =hourly cost of the land leveling machines (€/h) *a$_2$* =unitary maintenance leveling machine	Ncomp=Number of a equipment components Nirrig=annual number of irrigation events NLT=equipment component life time (years) ns=number of subunit per unit; Nsub=number of component replacements during NAP

time (h/ha)	Nu=number of units per field
b_0=distribution system fixed cost (e.g., valves) (€)	r0=reuse system fixed cost (€)
b1=unitary distribution system (dist.syst.) cost (€/m)	r1=unitary reuse system cost (€/ha)
FL =field length (m)	r2=unitary reuse system variable cost (€/m3)
FW =field width (m)	SUW=subunit width (m);
h_0=hourly cost of the man power (€/h)	t uexc=unitary machinery for cut volume (h/m3)
h_1=unitary man power time to install dist.syst. (h/m)	tap=application time (min)
h_2=unitary man power time to remove dist.syst. (h/m)	tMmin=additional time required to other tasks relative to irrigation (min);
h_3=unitary man power time to operate dist.syst. (h/m)	tuarea=unitary machinery time to land smoothing (h/ha)
IC= investment costs	Vexc=land leveling excavation volume (m3)
i_{TA}=annual interest rate (decimal)	VR=pumping reuse volume (m3/year)
NAP=analysis period (years)	

Table 4. Cost analysis equations

A water-yield function is used to estimate the crop yield from the computed total water use during the irrigation season. A quadratic function (Fig. 6) is adopted to calculate the relative yield (Y/Y_{opt}) from the relative water application (W/W_{opt}) (Solomon, 1984):

$$Y/Y_{opt} = k_0 + k_1 \cdot (W/W_{opt}) + k_2 \cdot (W/W_{opt})^2 + k_3 \cdot (W/W_{opt})^3 + k_4 \cdot (W/W_{opt})^4 \quad (8)$$

where W = actual water available for crop use during the irrigation season (mm); W_{opt} = seasonal water required for achieving maximum crop yield (mm); Y and Y_{opt} = crop yields (kg ha^{-1}) corresponding to W and W_{opt}, respectively; and k_i ($i = 1, ..., 4$) are empirical coefficients typical for the crop, and environmental and agronomical conditions under consideration. The decreasing branch of this function is related with soil drainage conditions and excess water impacts on yields. To consider these effects, the user should adjust to the local conditions the descending branch of the quadratic function, as indicated in Fig. 6 where 3 types of descending branches are presented.

The environmental attributes considered for selection of the design alternatives are:

1. The total irrigation water use during the crop season;
2. The nonreused runoff volume, that represents a nonconsumed and nonbeneficial fraction of water use and is an indicator for potential degradation of surface waters;
3. The deep percolation volume, which represents also a nonconsumed and nonbeneficial fraction of water use and is an indicator for potential degradation of ground waters;
4. The potential land leveling impacts on the soil quality; and
5. The potential for soil erosion.

The total water use, runoff and deep percolation volumes are calculated with SIRMOD for every single event of the irrigation season. The seasonal values are obtained by summing up these results. The attribute relative to land leveling impacts is expressed by the average cut depth because the smaller are the cut depths, the lower are the impacts on soil quality.
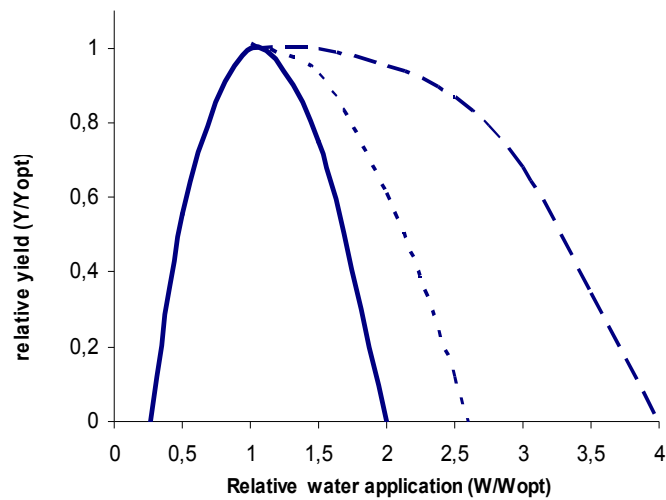
Fig. 6. Irrigation water-yield functions. Examples of quadratic equations with different descending branches for a crop susceptible to excess water in a poorly drained soil (—), for a susceptible crop in a drained soil (- - -), and for a non-susceptible crop in a well drained soil (— —)

The potential soil erosion attribute is a qualitative index, *EI*, which takes values 1-9 in an ascending scale of risk of soil erosion due to the applied irrigation water. *EI* is an empirical function of the inflow rate *q* per unit width or per furrow, the longitudinal slope S_o, and the soil type considering the empirical concept of maximum nonerosive inflow rate as proposed by Criddle et al. (1956). For furrows in a silt-loam soil, *EI* values relative to single events are given in Table 5 as a function of the product $q\,S_o$, where *q* in l s^{-1} and S_o in percentage. For different soil types this scale values should change similarly to the maximum nonerosive inflow rate. The seasonal *EI* is the geometric average of the single event values.

$q\,S_o$ (l s^{-1} %)	<0.30	0.3-0.5	0.5-0.62	0.62-0.75	0.75-0.87	0.87-1.0	1.0-1.25	1.25-1.5	>1.5
EI	1	2	3	4	5	6	7	8	9

Table 5. Potential erosion index *EI* for furrows in a silt-loam soil

2.3 Multicriteria analysis
The selection of the best irrigation design alternative is a multiple objective problem whose rational solution requires multicriteria analysis. This methodology integrates different types of attributes on a trade-off analysis, allowing the comparison between environmental and economic criteria (Pomerol & Romero, 2000). Multicriteria analysis supports a better understanding of the irrigation impacts while enabling us to achieve a satisfactory compromise between adversative decision-maker objectives.

The process starts with the definition of the design objectives and related attributes (Fig. 7). These attributes are then transformed into criteria through user-defined value or utility functions [Eqs. (9) and (10) presented below]. The alternatives and respective criteria are tabled in a payoff matrix, which synthesize the more relevant data for the selection analysis. A first screen of the alternatives may be done prior to the application of multicriteria using a dominance and satisfaction preanalysis.
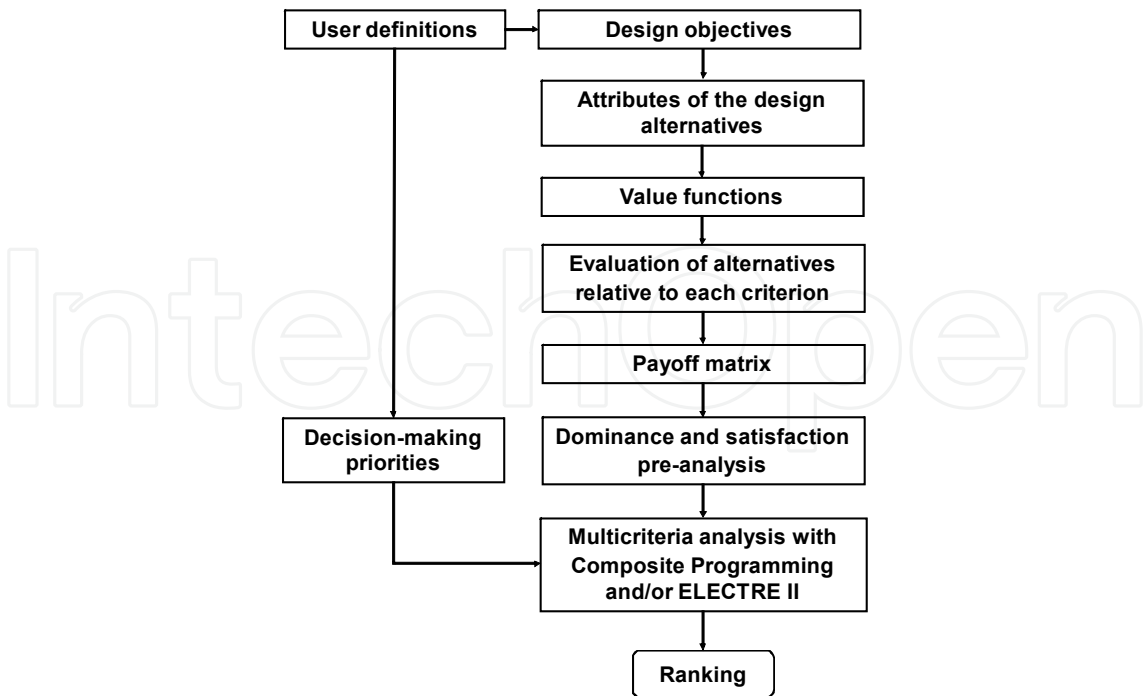
Fig. 7. Scheme of application of the multicriteria methodology

A set of design objectives and correspondent attributes are presented in Table 6.

Objectives	Alternative Attributes	units
Maximizing benefits	Yield value	€/year
Minimizing costs	Investment cost	€/year
	Operation and maintenance cost	€/year
Minimizing water degradation and the non-beneficial water use	Deep percolation	m³/year
	Runoff	m³/year
Maximizing soil conservation	Average land levelling cutting depth	cm
	Erosion index	index

Table 6. Objectives and attributes for design selection.

The decision criteria refer to:
1. Economic criteria relative to the yield value, the initial investment cost, and the operation and maintenance costs;
2. Environmental criteria relative to the potential degradation of groundwater and surface waters and the reduction of nonbeneficial water uses relative to tail-end runoff and deep percolation, potential erosion due to irrigation water flowing over the soil surface, and soil degradation due to land leveling cuts. Hydraulic criteria are represented in the environmental criteria through controlling runoff and percolation.

The attributes are scaled according to a measure of utility using value or utility functions, which are applied to the environmental and economic criteria. This approach enables to compare variables having different units, which is one of the primary benefits of multicriteria methodology. With this procedure, the utilities U_j for any criterion j are normalized into the [0-1] interval (zero for the more adverse and 1 for the most advantageous result).

The following linear utility function is applied for the economic criteria:

$$U_j(x_j) = \alpha \cdot x_j + \beta \tag{9}$$

where x_j = attribute: α = graph slope, negative for costs and positive for benefits; and the parameter β = utility value $U_j(x_j)$ for a null value of the attribute. A logistic utility function (Fig. 9) is adopted for the environmental criteria:

$$U_j(x_j) = \frac{e^{K_{bj} \cdot (x_{Mj} - x_j)}}{e^{K_{aj}} + e^{K_{bj} \cdot (x_{Mj} - x_j)}} \tag{10}$$

where K_{aj} and K_{bj} = function parameters; and x_{Mj} = maximum attribute value corresponding to a null utility for the j criterion.
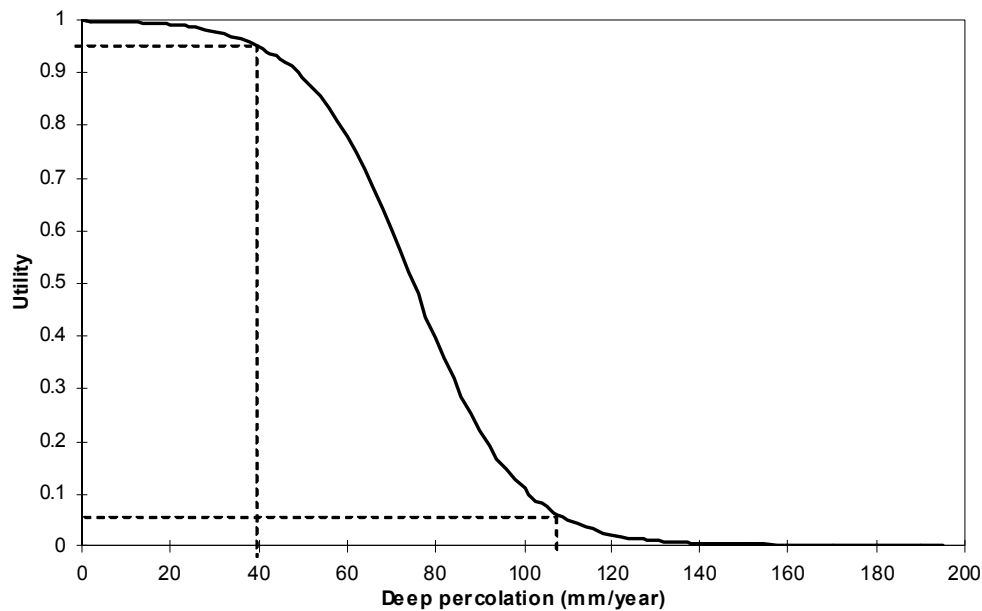
Fig. 8. Logistic utility function relative to deep percolation where x_a = 40 mm and x_b = 110 mm, and $U(x_a)$ = 0.95 and $U(x_b)$ = 0.05

To adjust this function (10) to user preferences, it is necessary to select the attribute values x_a and x_b that correspond to a very low and a very significant impact, e.g., such that $U(x_a) = 0.95$ and $U(x_b) = 0.05$, as shown in Fig. 8. Based on these values, and for a specific criterion, the parameters K_a and K_b are then calculated as follows (Janssen, 1992):

$$K_a = \ln\left[\frac{(1 - U(x_a)) \cdot e^{K_b \cdot (\alpha_M - x_a)}}{U(x_a)}\right] \tag{11}$$

$$K_b = \frac{\ln\left[\frac{U(x_a) \cdot (1 - U(x_b))}{(1 - U(x_a)) \cdot U(x_b)}\right]}{x_b - x_a} \tag{12}$$

The dominance preanalysis is a procedure to select the nondominated alternatives. For these alternatives do not exist any other feasible alternative that could improve the performance relative to any criterion without decreasing the performance of any other criterion. The multicriteria selection applies to those nondominated alternatives. The satisfaction preanalysis screens the alternatives set by selecting the user acceptable ones, i.e., those that for every criterion perform better than a minimum level required by the decision maker.

To apply the multicriteria methods, the user needs to assign priorities by selecting the weights λ_j that represent the relative importance of each criterion j as viewed by the decision maker. These can be directly defined by the decision maker or calculated by the Analytical Hierarquical Process (AHP) method (Saaty, 1990).

Two multicriteria methods may be applied: the composite programming (Bogardi & Bardossy, 1983) and the ELECTRE II (Roy & Boussiou, 1993; Roy, 1996). The composite programming is an aggregative multicriteria method that leads to a unique global criterion. It is a distance-based technique designed to identify the alternative closest to an ideal solution using a quasi-distance measure. This method allows the analysis of a multidimensional selection problem by a partial representation in a two dimensions trade-off surface.

The distance to the ideal point ($L_j = 1 - U_j$) relative to each alternative a_k, is a performance measure of a_k according to the criterion j. The ideal point represents the point on the trade-off surface where an irrigation design would be placed if the criteria under consideration were at their best possible level. If this distance is short, this performance is near the optimum. The composite distance L is computed for each set of N criteria as

$$L = \left[\sum_{j=1}^{N} \lambda_j \cdot L_j^p \right]^{1/p} \tag{13}$$

where L_j = distance to the ideal point relative to criterion j; and p = balancing factor between criteria. Each composite distance corresponds to a distance-based average, arithmetic or geometric, respectively when $p = 1$ or $p = 2$. The balancing factor p indicates the importance of the maximal deviations of the criteria and limits the ability of one criterion to be substituted by another. A high balancing factor gives more importance to large negative impacts (a larger distance to the ideal point) relative to any criterion, rather than allowing these impacts to be obscured by the trade-off process.

The ELECTRE II is an outranking method that aims to rank alternatives. It is based on the dominance relationship for each pair of alternatives, which is calculated from the concordance and discordance indices. The concordance represents the degree to which an alternative k is better than another alternative m. A concordance index is then defined as the sum of weights of the criteria included in the concordance set relative to the criteria for which the alternative k is at least equally attractive as the alternative m. The discordance reflects the degree to which an alternative k is worse than alternative m. For each criterion from a discordance set, that includes the criteria for which alternative k is worse than m, the differences between the scores of k and m are calculated. The discordance index, defined as the largest of these differences, reflects the idea that, beyond a certain level, bad performances on one criterion cannot be compensated by a good performance relative to another criterion. The decision maker indicates the thresholds that are used to establish a weak and a strong outranking relationship between each pair of alternatives.

For every project of a given field (Fig. 4), SADREG produces a large set of alternatives as a result of numerous combinations of design and operation variables. As mentioned before, these alternatives are clustered by groups relative to different water distribution equipment and tail end management options. The multicriteria analysis allows the alternative selection for each group and the ranking and comparison of the groups of a given project. This analysis plays an important role on automatic management of large amount of data, screening the alternatives, removing those not satisfactory or dominated, and ranking and selecting the most adequate according to the user priorities.

3. Web-based DSS methodology

The Web DSS application is based on client-server architecture. It comprises a Web module and a simulation engine, which includes the simulation models of SADREG (Fig. 9). The Web module controls the simulation engine, creates the user interface, importing and showing numerical and graphical data. The architecture of DSS Web Server and Client are schematized in Fig. 10 and 11. PHP and C# languages are applied to achieve higher system flexibility, and to minimize client system requirements. The SQLServer is applied for database management, which allows a simultaneous connection of several users. The server is established by four component modules, each one responsible for a task (Jia & Zhou, 2005): (1) Communication – the interface with the Web applications using TCP/IP like transport way; (2) Logic – the control of execution and respective data flow; (3) Simulation – the computation of simulation models; and (4) Data abstraction – the isolation and optimization data model and data modifications.
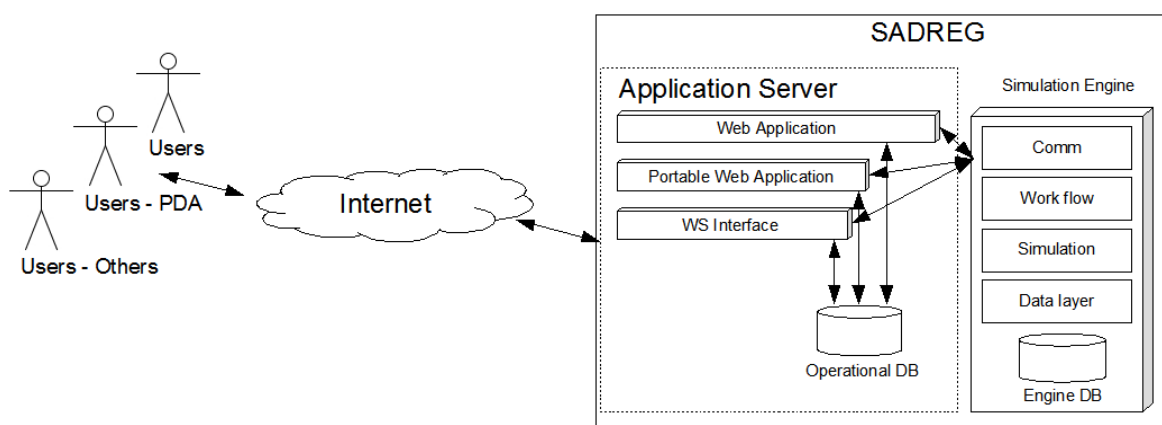
Fig. 9. Abstract system architecture

The application is multiuser, with properly warrant data protection among the several users. The user input data are provided to server that controls the simulation engine and return the output data to server that will be accessed by user. The software developed is based on first-in first-out philosophy, which uses a resources list that is being used and free up to the end of the simulation (Jia & Zhou, 2005). The communications with the server are performed in a first step of software development with TPC sockets, to avoid entropy. For normal system operation, a protection layer based on SSL protocol will be added for a better guarantee of communications security. The same procedure is adopted with the Web application that will use HTTPS connections. The protocol used in the communication with the server, without state and atomic operations, will be published to permit create other

applications based on this service. The user does not interact directly with the simulation engine to shorten the time required to complete the tasks. When the user requests a simulation, the order remains in a waiting list until the simulation engine is available to process it. Then the produced results are recorded in the simulation data base, the user is notified and the output becomes available on the Web application.
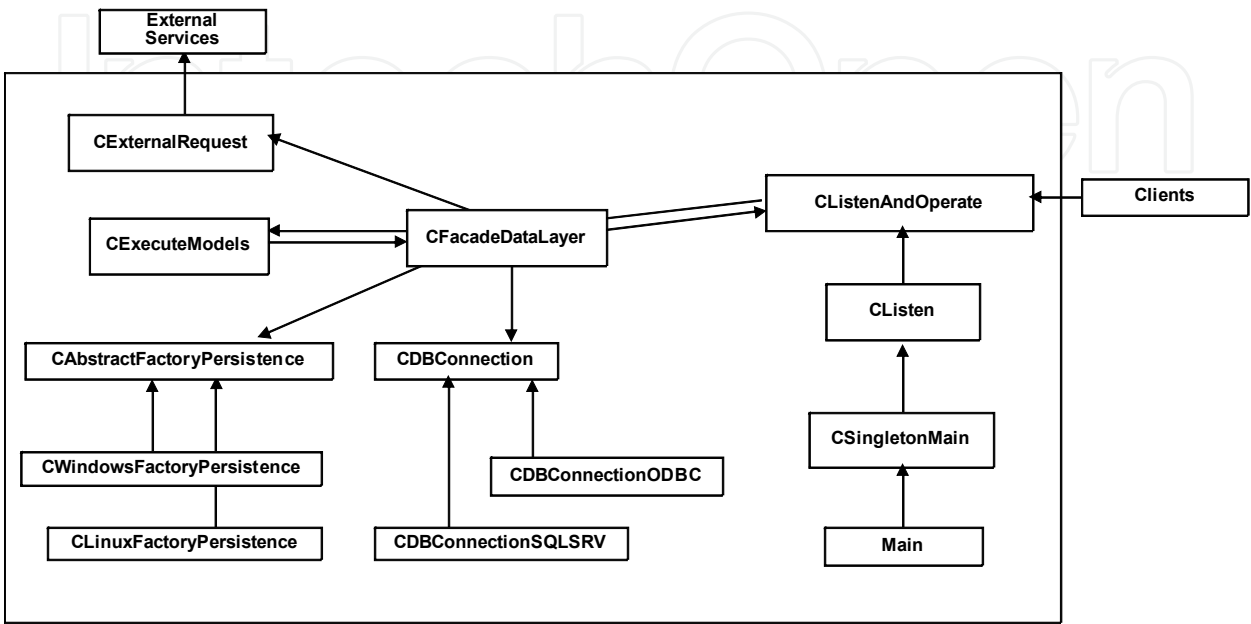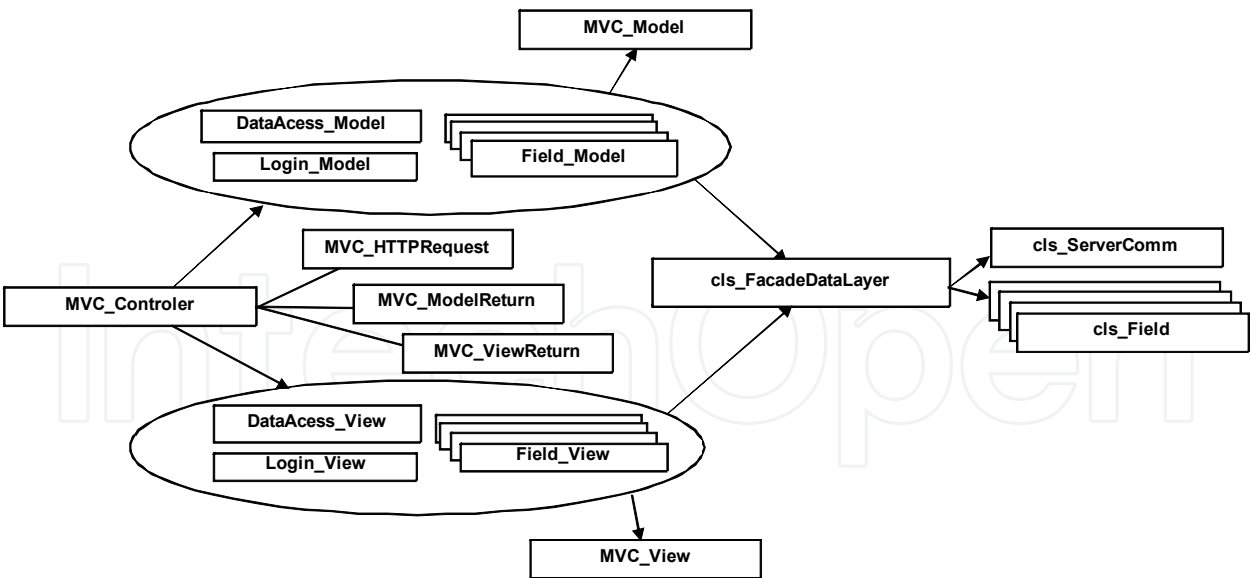

Fig. 10. Architecture of DSS Web Server

Fig. 11. Architecture of DSS Web Client

This approach confines the model relatively to Web system, allowing its reuse and maintenance without impact on system. This model could be transformed in a *stand-alone* application for off-line use. The database was designed to integrate all DSS information required, from agronomic, climatic and economic subjects. All records had specialized information to provide auditoria and controls of permissions, allowing the possibility to

share data and experiences by groups of users. The access control to user data is guaranteed at level of server. In the server the data abstraction is provided by pattern AbstractFactory (Fig. 12) to guarantee without impact on models source code a platform change. The communications with server are made with TCP/IP sockets applying a protocol developed specifically. The use of norms like SOAP and WebServices will be included, in a higher layer, like a protection SSL layer, with a guarantee of security, without state and atomic operations, will be published to permit create other applications based on this service.
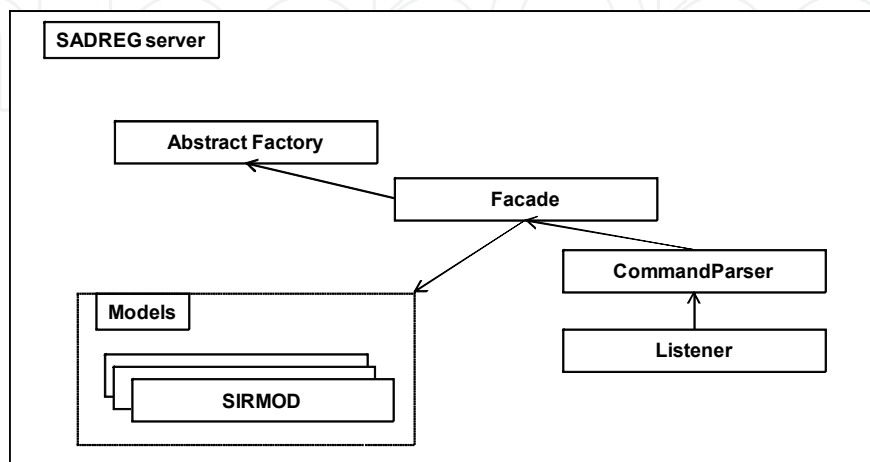
Fig. 12. Models integration on DSS Web server.

The interface includes a context online help, allowing a direct support to users. It was created a simple Web user friendly interface. The user may select the language of the interface. The system has available also a Web-service interface to integrate with other systems and a short Web version to be used with portable and limited equipments, such as PDA for field use.

4. Applying the DSS

The data flow and logic of the execution are represented in the diagram of Fig. 13. To access the application the user needs to register beforehand asked the system administrator, with the conditional access by keyword. The interface language is set in the attributes of the user, although this may change in a straightforward manner by clicking on the button.

4.1 Input data

The user can view the general options of the application, without change them, because these data are the responsibility of the administrator. These data include, for example, the technical characteristics of equipment for water supply, the classification of soils (example in Fig. 14), climatic stations and the curves of infiltration. These data will be accessed during the timely preparation of projects. In turn, the user data comprises its private information, which may have access to the group member's share with which the user has set permission. The field is the subject of spatial unit design, and its register, inserted in the field workspace, includes features such as location, soil type, and size and topography data (Fig. 15). A user can create multiple field workspaces, from a new record or copy of an existing one. Other user data refers to crops and unit costs, which may well be applied in different fields of the same user.
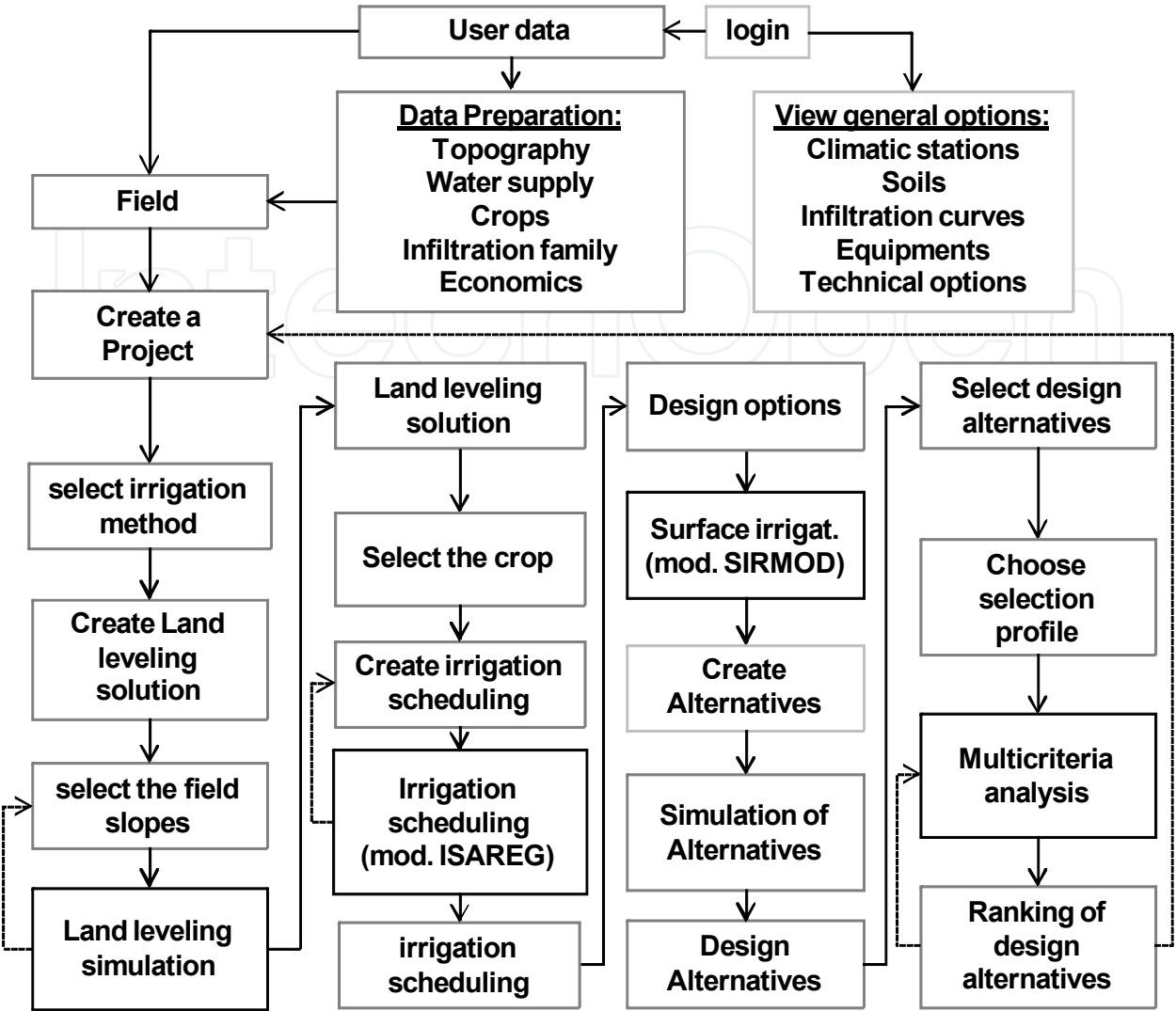
Fig. 13. Data and simulation flowchart

4.2 Projects

Once the user has completed the field data register, he(she) builds projects to create alternatives. Each project refers to a particular method of irrigation and a land leveling solution. This solution is obtained by simulation the land leveling, using the field topography of the parcel and the slopes selected by user. The user will have access to the simulation results, which included the volumes handled, the spatial distribution of the depths of excavation and fill and the estimated time of execution of work and its cost. Interactively, the user can do several simulations to find a solution that he(she) considers appropriate for the project.

In the next step, the user chooses a crop to be considered in the project within a list of options. The determination of the irrigation scheduling, i.e., the appropriate application depths and the irrigation dates along the crop period, is obtained with the ISAREG model. This calculation requires the application of climatic data from the region where the field is located, and information about the type of soil and crop characteristics. This process is also interactive with the user, because there are several possible solutions to these calendars. The user will then choose the one more appropriate to the project.
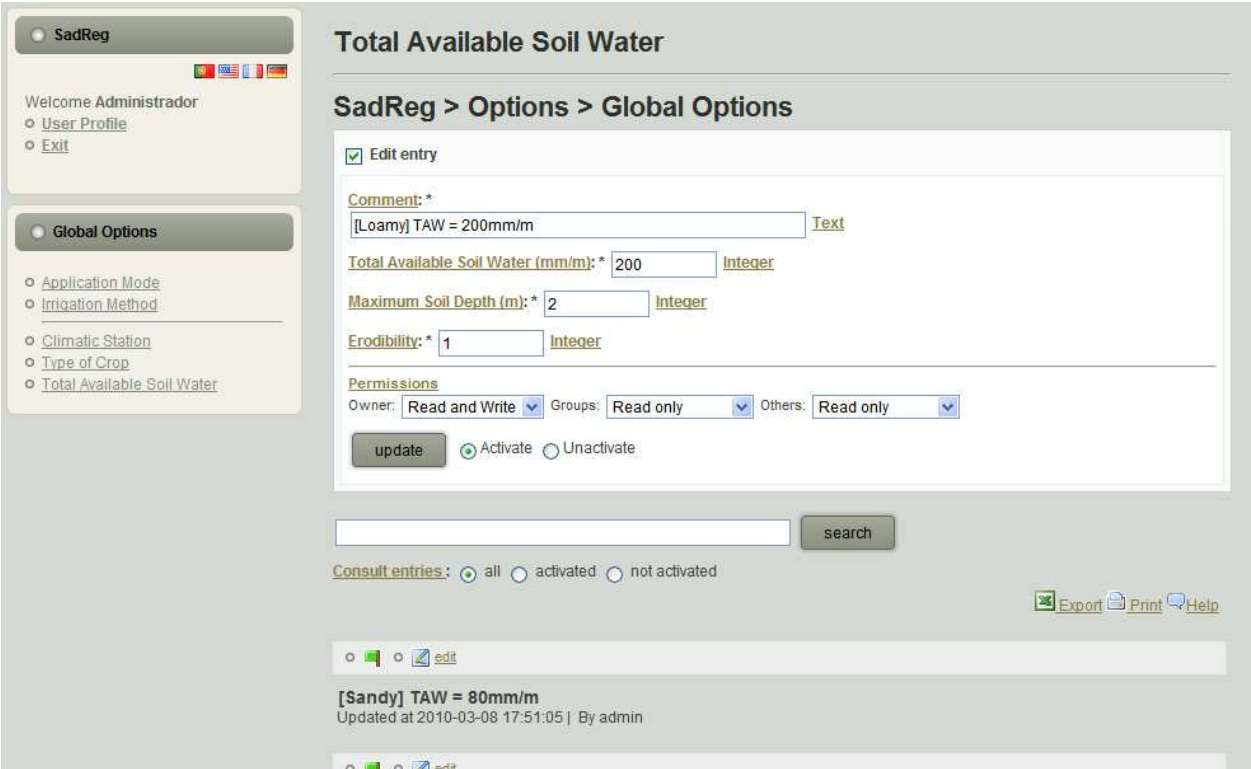
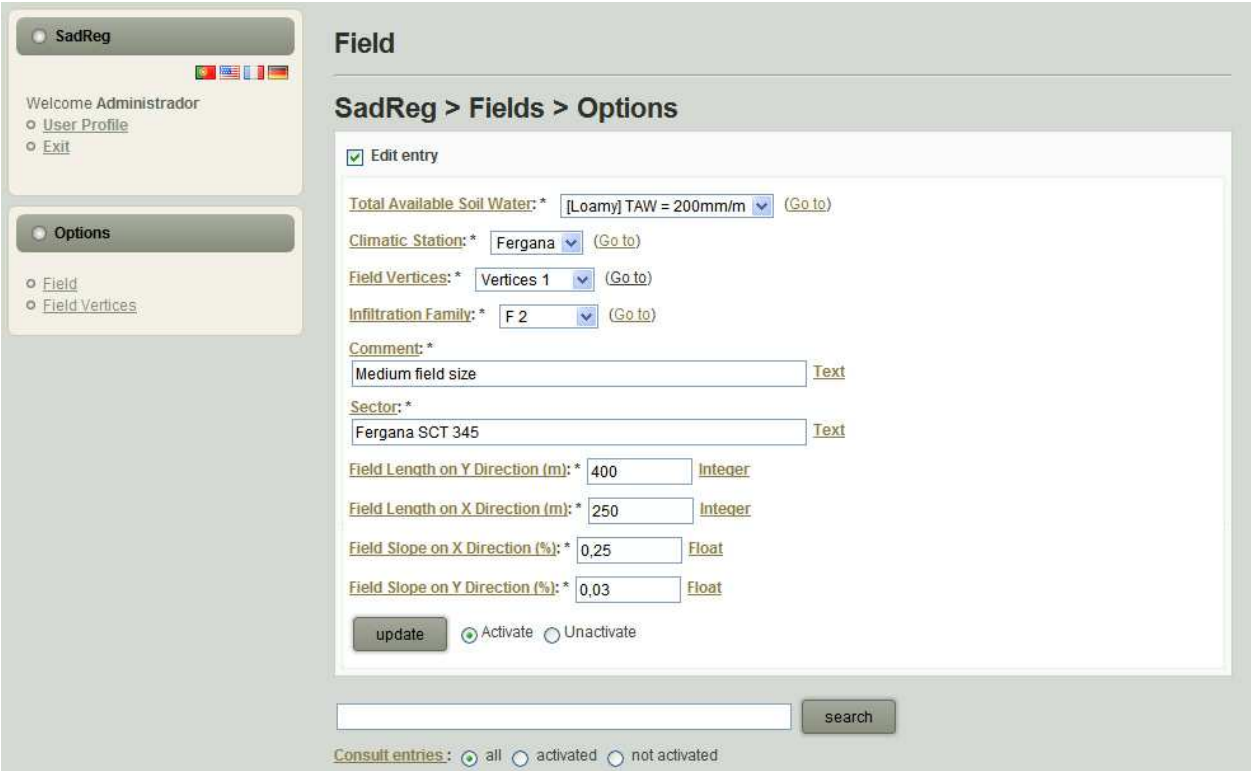Fig. 14. Example of view access to general options data on Web interface (example of soil type)

Fig. 15. Example of field input data on Web interface

4.3 Design options

The user sets the project options that will be applied in creating alternatives. These options relate to supply conditions, such as surge or continuous inflow, possible field subdivision in the longitudinal and cross directions, equipment for water distribution (e.g., gated pipes or canals), the flow conditions at the downstream end (e.g., open, closed or re-use), and the constraints in supplying water to the field (flowrate, hydraulic head, frequency). Then the application runs the model SIRMOD for hydraulic simulation of the process of irrigation or access to previously recorded results, if they exist in the database, and then proceeds to create alternatives. The user then accesses the results, refering the projects and groups (Fig. 16), view and analyses the alternatives developed (Fig. 17), and may remove them when they are unsatisfactory.
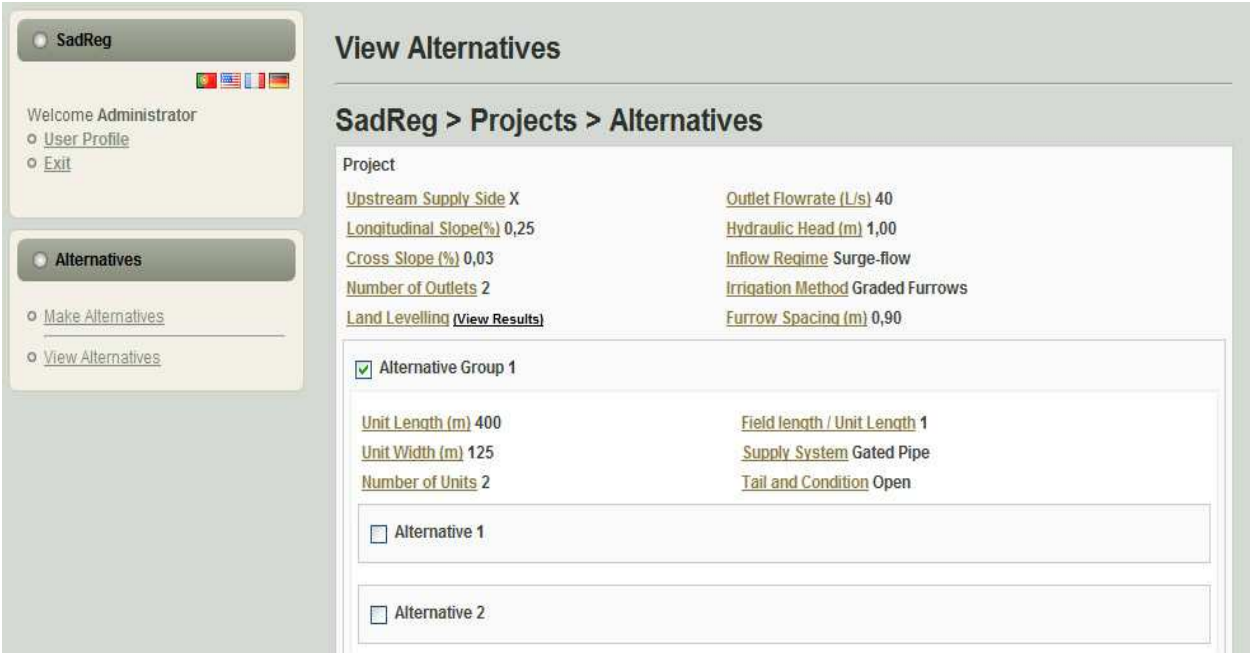
Fig. 16. Example of project results view on Web interface

4.4 Selecting alternatives

The next step is the selection of design alternatives through the module using multicriteria analysis (MCA). For this purpose the user must set the profile to apply for selection (Fig. 18), which is the set of multicriteria analysis parameters, such as the method, the value functions associated with the attributes, the decision criteria and corresponding weights defining the user priorities. The results will include the identification of effective alternatives, i.e., those that have enough quality to be selected, and the unsatisfactory or dominated, i.e., the ones that are not considered for the subsequent ranking of alternatives. This process is interactive with the user, which could generate new rankings when changing the profile selection.

Once this process is ended, the user has information to make the decision, thus choosing the alternative which he(she) prefers to see implemented, or, the user may seek for another solution to the problem by creating a new project, thus changing any of the options made. This iterative process is controlled by the user, resulting in increased number of design alternatives, which may be all together analyzed and ranked by the MCA module.
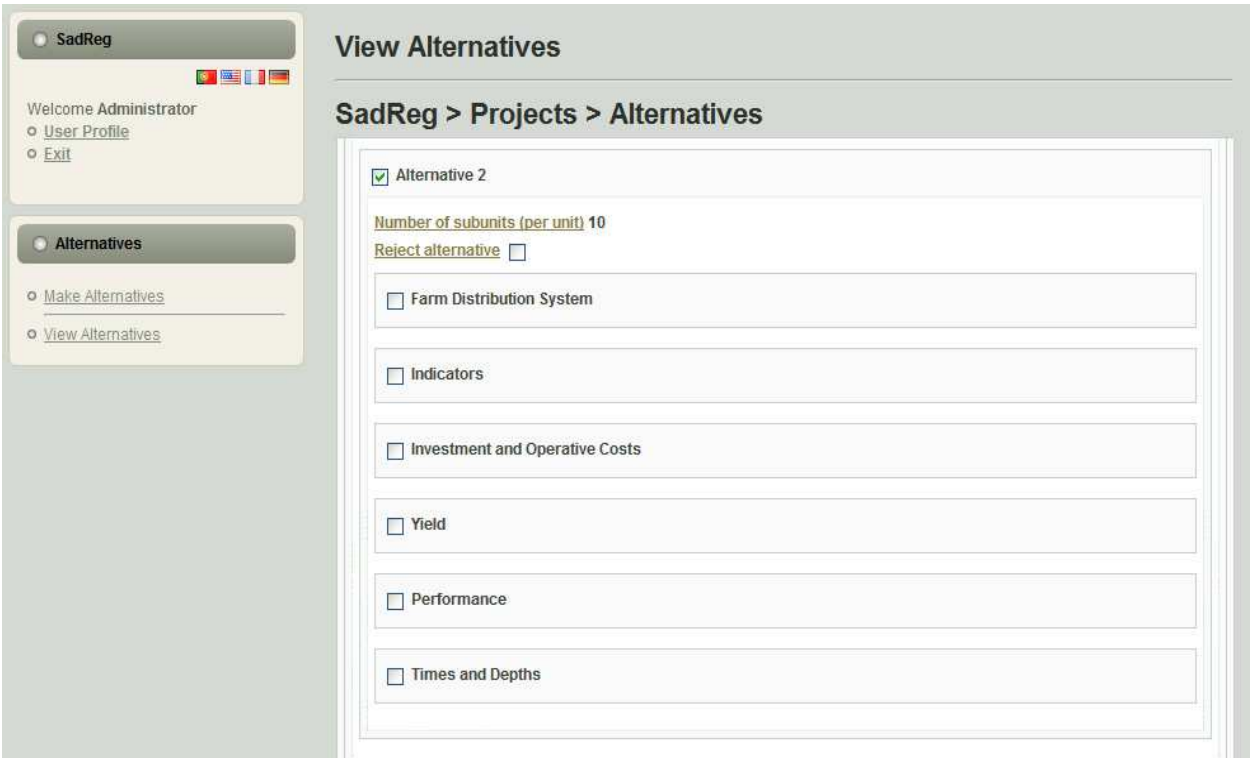
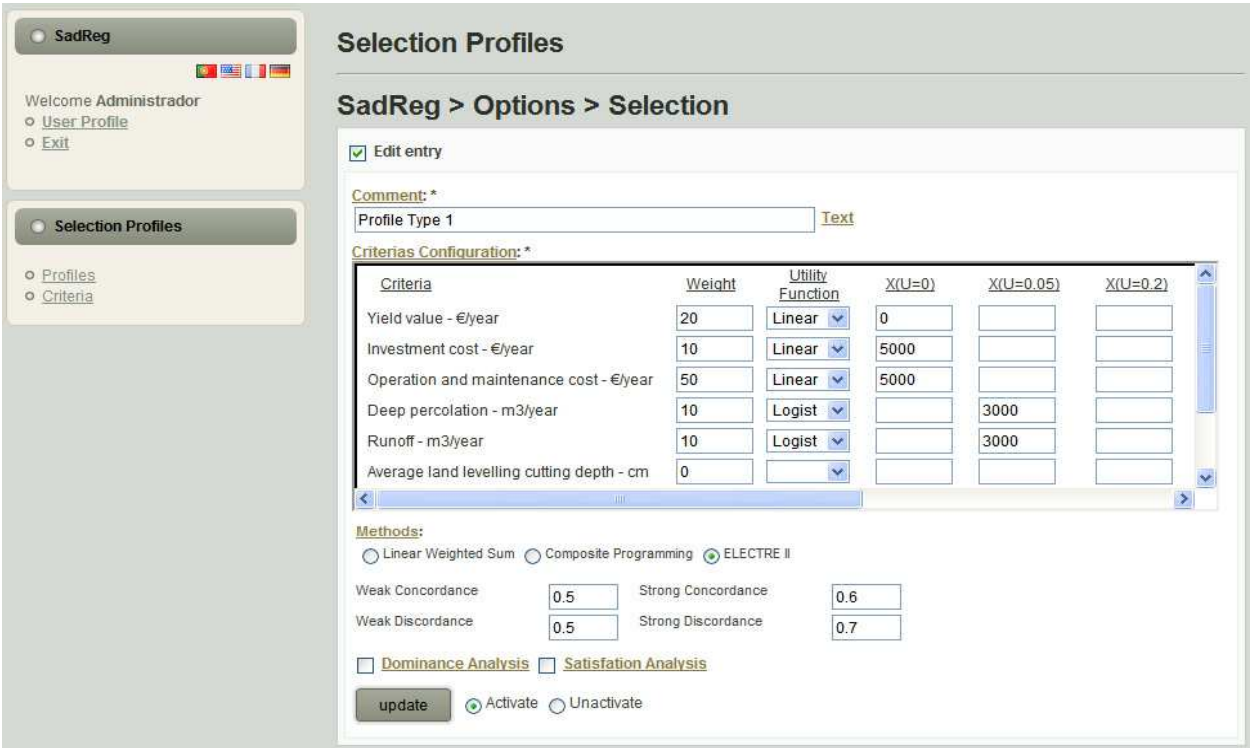Fig. 17. Example of alternative view on Web interface, showing the main results itens

Fig. 18. Example of selection profile definition on Web interface

5. Conclusion

Appropriate design of surface irrigation systems requires a complex manipulation of data, models, and decisions. The multicriteria approach integrated in a DSS enables us to solve that complexity while creating and ranking a large number of design alternatives. The DSS SADREG has shown to be an appropriate tool for (1) generating design alternatives associated with attributes of technical, economic, and environmental nature; (2) handling and evaluating a large number of input and output data; (3) evaluating and ranking design alternatives using multicriteria analysis where criteria are weighted according to the priorities and perception of the designer and users; and (4) providing an appropriate dialogue between the designer and the user.

The Web-based DSS allows a simple way to support surface irrigation designers to improve the project procedures, particularly in the world water scarcity areas where the surface irrigation requires improvements and the expert technical support is more incipient. With a simple Web user friendly interface, with several optional languages and an online help, this tool would contribute to an effective support to enlarge the knowledge of surface irrigation, its design procedures and field practices.

In conjunction with web application SADREG, tools are available towards the resolution of specific problems such as land leveling, pipe sizing and economic calculation, as well as documents on good equipment and irrigation practices. The application maintenance and user support is the responsibility of the multidisciplinary team that developed the software, with computer engineers and agronomists, the objective being that of a dynamically adjusts the system to answer the most frequent difficulties and new challenges more exciting. This software is available on http://sadreg.safe-net.eu Web site.

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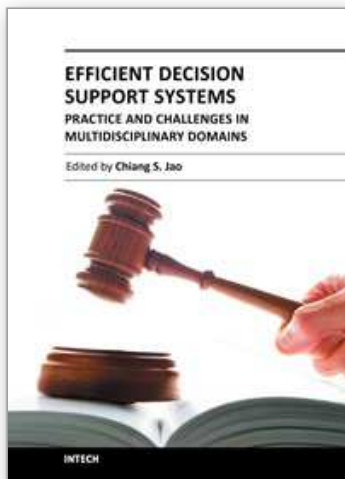
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