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EXECUTIVE SUMMARY

The overall aim of OPTIMA is to develop, implement, test, critically evaluate, and exploit an innovative, scientifically rigorous yet practical approach to water resources management, in close cooperation with local and regional stakeholders, intended to increase efficiencies and to reconcile conflicting demands. Based on the European Water Framework Directive (2000/60/EC), the approach equally considers economic efficiency, environmental compatibility, and social equity as the pillars of sustainable development. The project realises both the importance of the socio-political and economic aspects, but also the importance of a reliable, consistent, and shared information basis for the policy and decision making process.

The central analytical paradigm in OPTIMA is optimization, based on a dynamic water resources model system describing a river basin in terms of water demand and supply, technical and hydrological efficiency, access and reliability, costs and benefits at various levels of sectoral and spatial or temporal resolution and aggregation. The optimization approach operates on several closely integrated levels with the appropriate feedback cycles and continuous stakeholder involvement.

OPTIMA uses a multi-stage procedure with a two-stage optimization approach specifically designed to facilitate a participatory approach and continuing stakeholder involvement:

1. A first phase builds a detailed model representation of the water resources system under study and establishes a baseline scenario for each case study;
2. A second phase based on evolutionary algorithms for complex optimization identifies feasible solutions that meet all or as many as possible of the user expectations expressed in terms of constraints on performance criteria;
3. A subsequent discrete multi-criteria phase is oriented toward conflict resolution: it defines the trade-offs between the conflicting objectives using a reference point methodology and the concept of Pareto-efficiency to arrive at a generally acceptable solution as global optimum.

This report describes background and implementation of the discrete multi-criteria approach for conflict resolution that is designed for direct stakeholder participation.

Project technical objectives

The primary general objectives of the Programme include: Developing comprehensive Decision Support Systems (DSS) through the use of area wide Geographical Information Systems (GIS) combined with remote sensing capabilities in support of policy analysis and enforcement as appropriate.

Within this more generic framework, **OPTIMA** addresses a number of specific scientific objectives:

- To build, and test in a number of parallel comparative case studies, a consistent and well integrated set of advanced but practical DSS tools for efficient, "optimal" water management strategies and policies of use, designed for a participatory public decision making process.
- To extend the classical techno-economic approach by explicit consideration and inclusion in the two-phase optimisation methodology of acceptance and implementation criteria, where the method not only helps to generate optimal solutions, but facilitates the process of agreeing on what exactly optimal means in any particular case, as a shared community vision, including gender sensitive issues where feasible.
- To develop a generic approach to combine engineering analysis and formal optimisation with socio-economic considerations in a unifying and consistent multi-criteria multi-objective framework.
- To integrate expert systems technology and heuristics with complex simulation and optimisation models to improve their usability in data poor and data constrained application situations.
- To develop appropriate tools and methods for the communication of complex technical information to a broad range of participants and stakeholders in the policy making process, based on classical workshops and Internet technology, and in particular the easy and efficient elicitation of preferences and trade-offs in an interactive, reference point approach.
- To adapt and further develop formal methods of optimisation for highly complex, non-linear, dynamic, and spatially distributed systems that are non-differentiable by applying heuristics, genetic programming combined with local stochastic gradient methods and post-optimal analysis for large scale discrete multi-criteria problems.

WP3: Objectives

Objectives:

The main objective is to adapt and implement, based on the findings of WP 01, a set of quantitative analysis tools (simulation and optimisation models) that are easy to use with the available data, computationally efficient, and that can provide a realistic, comprehensive problem representation. The objectives include:

- Adaptation and implementation of the water resources management simulation model;
- Adaptation and implementation of the optimisation framework (heuristics and genetic programming)
- Linkage of the simulation model system with the optimisation framework;
- Adaptation of the interactive discrete multi-criteria optimisation module.
- Adaptation implementation of a rule-based assessment model.

Tasks:

This includes adaptations of the software (the basic components are available as operational prototypes), installation with the basic data sets from the case studies (resulting from the parallel compilation of generic techno-economic data in WP 04 and the individual case study data), documentation and user training, and preparation for the optimisation scenarios for WP07-WP18. A major task is the building of the necessary interfaces between the components (simulation model, expert system, and the optimisation framework), the integration of the economic assessment (NPV calculations) with the basic simulation model, and the rule-based expert system for the assessment of environmental, and social criteria for the optimisation.

Specific tasks include:

- Adaptation of the model system according to the user requirements of WP 01;
- Fine tuning of the genetic programming algorithms to improve computational performance and add the rule-based assessment components to the objective function and constraints;
- Preparation of linkages between the components based on a standard interface and protocol, using a three-tier client server architecture to facilitate web access;
- Integration of economic assessment (NPV of water supply and use, costs and benefits);
- Integration of the basic simulation/optimisation model with the discrete multi-criteria optimisation tool.
- Adaptation of the interactive user interface for the discrete optimisation approach to support web access with standard, ubiquitous and familiar web browser software.

Decision Support Systems: concepts and terminology

There is no single accepted definition of what constitutes a Decision Support System (DSS) in the technical literature. There are, however, a few common traits in most definitions as the examples below demonstrate:

A decision support system (DSS) is both a process and a tool for solving problems that are too complex for humans alone, but usually too qualitative for only computers. Multiple objectives can complicate the task of decision-making, especially when the objectives conflict. As a process, a DSS is a systematic method of leading decision-makers and other stakeholders through the task of considering all objectives and then evaluating options to identify a solution that best solves an explicit problem while satisfying as many objectives as possible to as high a degree as possible (Westphal, K. 2000).

"Decision support system" is defined as an approach or methodology for supporting decision-making. It uses an interactive, flexible, and adaptable computer-based information systems especially developed for supporting the solution for a specific non-structured management problem. It uses data, provides an easy user interface, and can incorporate the decision maker's own insights. In addition, a DSS usually uses models and is built (often by end users) by an interactive and iterative process (evolutionary prototyping process). It supports all phases of decision-making and may include a knowledge component. Finally, a DSS can be used by a single user on a PC, or it can be Web-based for use by many people at several locations. (Turban et al. ,2001).

In summary, a DSS is computer based, including hardware, software, and data; it must assist in making non-trivial decisions, but beyond that, there is little agreement. Analysing the literature, the overwhelming number of cases that claim DSS status refer to relatively simple information and model systems that focus on problem representation and in most cases, WHAT-IF type scenario analysis.

A considerably smaller group addresses optimization tools with usually a strong Operations Research and mathematical programming focus.

The basic functions of a DSS include:

1. Identify and structure the problem, and define a consistent preference structure in terms of criteria, objectives, and constraints.
2. Design alternatives that provide solutions to the problem as posed.
3. Select preferred solutions from the set of alternatives based on the preference structure.

The main elements of a decision include the design of promising, feasible alternatives and the subsequent selection of a solution (alternative) from a set of alternatives thus generated or identified. This decision process is based on:

- A set of **Alternatives**, which can be discrete and pre-existing, or generated on demand;
- A set of **Criteria** describing each of the alternatives; criteria can be qualitative or quantitative, cardinal, ordinal or nominal.
- **Constraints** describing acceptable lower or upper bounds on any one of the criteria; only a solution that meets all constraints is deemed a feasible alternative and subsequently considered.
- **Objectives** or objective function(s), expressed in terms of the criteria that should be minimized or maximized by the selection

- A **preference structure** that defines the relative importance of different criteria in contributing to the objective function, and the different importance of different objectives in an overall evaluation.

The choice or selection project can be dynamic (in time) or static, include spatial properties, and use dynamically generated attributes (from simulation models or on-line monitoring) in the analysis.

There are several basic decision oriented processes that DSS tools can support:

- **Classification, estimation.** Given contextual or anecdotal information, an estimate for an unknown or its classification is derived by inference. The method is first order logic, the implementation a backward chaining rule-based expert system. Given a target concept, a set of rules guides the user to a best estimate or classification for the variable or symbol sought. Examples are the estimation of model parameters, complex estimates using cascading heuristics (e.g., the arrival time of a first-responder team at a given accident location) or the classification of an event given limited information (e.g., the level or severity of an accident and the corresponding alarm level). A typical example is an EIA procedure (<http://www.ess.co.at/EIA>), or numerous elements in quantitative risk analysis and assessment: <http://www.ess.co.at/RISK>.
- **Operational advise** in real-time. The same basic principle holds for operational or tactical advice in real-time, e.g., for emergency management. These systems are referred to as IC3 (Intelligence, Communication, Command, Control). Any set of formal, consistent guidelines or operating procedures can be implemented as rules, and processed to provide decision support in the form of operational instructions in a dynamically changing context with asynchronous information flow. However, real-time may also span days and weeks rather than minutes and hours, e.g., to control a multi-step procedure like an EIA process. The method is again based on rule-based expert system, but combining forward-chaining with backward chaining, so that the inference engine runs continuously in real-time and considers time or time derived variables (absolute time, simulated time, elapsed time, etc.) among the decision criteria. Typical examples are technological and environmental emergency management systems (<http://www.ess.co.at/HITERM/>) or on-line technical training (<http://www.ess.co.at/A-TEAM>) for emergency management.
- Within the framework of OPTIMA, reservoir release in anticipation of a flood based on upstream precipitation patterns and high-flow conditions would be an example of operational, real-time tactical decision support.
- Multi-criteria **Ranking and Benchmarking.** Given a set of objects each described by multiple attributes or criteria (e.g., chemical plants, areas at risk, slopes prone to landslides) the system supports the interactive ranking of the set by any or all of the criteria in any arbitrary combination. The objective is to establish a rank-order by dynamically generated, derived criteria the user defines interactively. An example from regional planning is <http://www.ess.co.at/NOE/Edemo.html>. The benchmarking concept introduces a context for evaluation, and relative positioning of objects in relation to known reference cases rather than isolated and in more difficult to interpret absolute terms in the absence of general standards that can be used as constraints.
- **Complex Optimization.** In the previous cases the set of alternatives were supposed to be given. If we have a model or set of models describing a complex system, we can generate any number of alternatives, and apply the above elements to identify a best, most desirable solution, and in fact design it automatically to meet all constraints and minimize or maximize the objective functions. Since large, complex system are usually non-differentiable unless simplified considerably, and all observations are highly uncertain (especially in the risk analysis domain) we extend the set of criteria by elements of

Gestalt and measure similarity in term of distance in a N dimensional behavior space. The underlying methodology is a hybrid of several heuristic methods, including Monte Carlo, stochastic hill-climbing, linear and dynamic programming, and evolutionary algorithms to make the search procedure more efficient and avoid computability issues of combinatorial explosion. However, for large systems, the method is very compute intensive, which is the price for a detailed and more realistic model description (coupled, dynamic, spatially distributed, non-linear).

- **Discrete MC Optimization.** This is an implementation of the reference point methodology of multi-attribute theory. Its basic advantage is simplicity, the use of a minimum set of assumptions, so that it lends itself to interactive use. Here we use the N dimensional geometry of the behavior space (defined by the set of alternatives) to define measures of achievement (the objective function) given the distance of any alternative from utopia, or a user-defined reference point. The implicit normalization of the criteria (dimensions) to the interval between nadir and utopia as a degree of (possible) achievement makes it possible to use an effective strategy without eliciting complicated weights or preferences from the user. The method first partitions the search space into dominated and non-dominated alternatives (i.e., generating a Pareto-optimal sub-set) always depending on the user's choice of the criteria to be considered, and any constraints specified.

Scenarios: the repertoire to choose from

The basic logic of a discrete (multi criteria) decision support approach is simple: a set of possible alternatives for the systems behaviour is generated (by various modelling techniques) each representing an alternative control or management strategy leading to a corresponding performance of the system. This performance is described in terms of criteria that can be evaluated and compared (explicit or implicit trade offs) to arrive at a final preference ranking of the alternatives and an eventual choice of a preferred alternative as the solution of the Decision Process. This set of alternatives to choose from can be generated within a single, or several alternative sets of scenarios of assumptions on uncontrollable external variables (in OPTIMA, this mainly refers to assumptions about demographic development and on climate change, expressed in the baseline scenarios). However, it is important to remember that these assumptions on uncontrollable external factors are not subject to choice and thus the decision making process.

Multi-criteria, multiple and conflicting objectives

An objective is something that a decision maker seeks to accomplish or to obtain by means of his decision. A decision maker may have more than one objective (the MULTIPLE-OBJECTIVES case).

An objective may be specified in a more or less general fashion, may be quantified or not quantified, and is usually part of a hierarchy of objectives. The term goal is sometimes used to denote a very general objective (at the top of the hierarchy) and TARGET is used to mean a very definite objective. Example: "The goal of allocating money to the municipality was to increase the quality of urban life. The immediate objectives were to improve public transportation and fire services. A 10% reduction of average travel time from home to work and a 70% decrease of average alarm-to-action time taken by the fire brigades were set forth as targets."

The multiple objectives of a single decision maker are usually COMPETITIVE: i.e. the improvement in one of them is associated with a deterioration in another (usually because of limited resources or because of other constraints). Competitive objectives are sometimes referred to as CONFLICTING objectives. However, one should speak about a conflict and about conflicting objectives only if there are two or more decision makers who have different objectives and who act on the same system or share the same resources. In the example given above, the director of urban transportation and the director of city fire services have conflicting objectives. At the same time, the mayor of the city, if he were the single decision maker, would look at these objectives as competitive. If the two directors are left without a coordinating influence by the mayor (who would, for example, decide how to allocate the resources), a CONFLICT SITUATION may result. With the mayor's interventions, the system becomes a hierarchy of decision makers, and the conflict may be resolved. When the extent to which an objective is attained is measurable on some appropriate scale, one can speak about the degree of attainment of the objective. In systems analysis, one often uses [PROXY OBJECTIVES:] objectives other the original ones, but such that are measurable and can be quantitatively discussed. A proxy objective should at least point in the same direction as the original one; for example, "reduction of mean travel time" in urban transportation is a proxy for "improved services." In a mathematical description, the measures of the multiple objectives Q_1, Q_2, \dots, Q_n are considered to be coordinates of a point in the n -dimensional OBJECTIVE space. Then, the TARGET values T_1, T_2, \dots, T_n prescribed for the n objectives are considered to be coordinates of the TARGET POINT in this space. When the target value requirements are set forth as some intervals rather than single Numbers, they define a region in the objective space that is referred to as a TARGET SET.

Discrete Multi-criteria optimization

The first phase of the optimization process (see Deliverable D03.2) is based on a complex water resources simulation model (Deliverable D03.1). It can generate one or more feasible solution. In the former case the choice is easy: Hobson choice suggests itself.

If there are more than one feasible solution, a second selection process has to be used to identify a preferred solution from the set of feasible alternatives with multiple criteria. This is a classical discrete multi-criteria decision problem (Bell, Keeney & Raiffa, 1977).

Multi-attribute theory: multiple objectives and criteria

Any non-trivial real-world decision problem involves multiple criteria that describe the alternatives, and are used to express constraints and objectives, and usually also multiple, and often conflicting objectives.

Consider a simple abstraction (based on the introduction to “Conflicting Objectives in Decisions” by Bell, Keeney and Raiffa (1978):

A decision involves the choice between alternatives $A_1 \dots A_n$; These are described by a set of attributes $X_1, \dots, X_j, \dots, X_n$, and each alternative A_i can be described in terms of these attributes or criteria. Thus choice or alternative A_i can be described with the attribute vector $X_i = (x_{i1}, \dots, x_{ij}, \dots, x_{in})$.

The attribute set X is not given a priori. Its selection and definition is one of the most critical steps in the decision making process. It can easily be demonstrated that adding or deleting criteria from consideration is a very powerful way to influence decisions. Once the vector is defined, the task is to measure the distance, in some sense, of each alternative (a point in this criteria hyperspace) to the decision maker's expectations or aspirations – this involves the problem of scaling incommensurate dimensions.

The primary concern is to make sure the criteria are relevant, that is they describe aspects of the decision problem that are indeed meaningful and relevant to all stakeholders and actors. This invariable will lead to the fact that are incommensurable, i.e. they have very different units that can not be readily converted. The criteria will also include intangibles that are not amenable to direct measurement but may reflect psychological or aesthetic considerations, beliefs, fears, perceptions which are extremely difficult to measure or elicit and scale. The problem of environmental valuation, but also the cost or the value of human life are typical, and usually controversial examples.

Water resources management decisions may have a considerable life time. Their consequences evolve over time. Beyond introducing uncertainties about future boundary conditions (for example, energy prices) this leads to considerations of intergenerational effects or trade-offs. Requirements for long-term equity and sustainability will an additional dimension.

Goal programming and the satisficing paradigm

Reference point approaches might be seen as a generalization of goal programming. They were developed later than goal programming, starting with research done at the International Institute for Applied Systems Analysis (IIASA) in Laxenburg near Vienna, Austria, specifically as a tool of environmental model analysis, although these approaches have found applications also in engineering design and other fields of decision support since that time. In parallel, similar or equivalent approaches were developed, e.g. the weighted Chebyshev procedure by Steuer and Cho (1983) or the satisficing trade-off Method by Nakayama and Sawaragi (1983). Later, Korhonen and Laakso (1985) draw the attention to the fact that reference point methods can be considered as generalized goal programming. This generalization tries to preserve main advantages of goal programming and to overcome its basic disadvantage.

The main advantages of goal programming are related to the psychologically appealing idea that we should set a goal in objective space and try to come close to it. Coming close to a goal suggests minimizing a distance measure between an attainable objective vector (decision outcome) and the goal vector. The basic disadvantage relates to the fact that this idea is mathematically inconsistent with the concept of vector-optimality or efficiency. One of basic requirements { a general sufficient condition for efficiency { for a function to produce a vector-optimal outcome (when minimized or maximized) is an appropriate monotonicity of this function. But any norm, representing the concept of a distance measure, is obviously not monotone when its argument crosses zero. Therefore, norm minimization cannot, without additional assumptions, provide vector-optimal or efficient solutions.

According to Simon, real decision makers do not optimize their utility when making decisions, for many reasons. Simon postulated that actual decision makers, through learning, adaptively develop aspiration levels for various important outcomes of their decisions. Then they seek decisions that would result either:

In outcomes as close as possible to the aspiration levels, if the latter are not attainable (which corresponds to an optimization of decisions, but in the sense of the distance from aspiration levels);

In outcomes equal to aspiration levels, if the latter are attainable (which corresponds to stopping improvements in this case).

We see that satisficing decision making can be in fact mathematically represented by goal programming. Thus, reference point optimization is a generalization of the goal programming approach to such cases when we can and want to improve (minimize or maximize) certain outcomes beyond their reference points, which is a commonly observed behaviour in negotiation situations.

Discrete multi-criteria methods

Since each scenario is described by more than one performance variable or criterion, the direct comparison does not necessarily result in a clear ranking structure: improvements in some criteria may be offset by deterioration in others. This can only be resolved (and resulting in an eventual ranking and selection) through the introduction of a preference structure that defines the trade-offs between objectives.

The basic optimization problem can be formulated as:

$$\min F(x), x \in X_0$$

where

$$x = (x_1, x_2, \dots, x_n); x \in \mathbb{R}^n$$

is the vector of decision variables (the scenario parameters), and

$$f(x) = (f_1(x), f_2(x), \dots, f_p(x)) \in \mathbb{R}^p$$

defines the objective function. X_0 defines the set of feasible alternatives that satisfy the constraints:

$$X_0 = \{x \in \mathbb{R}^n \mid h_1(x) \leq 0, \dots, h_k(x) \leq 0\}$$

In the case of numerous scenarios with multiple criteria, we can define the partial ordering

$$f(x^1) \leq f(x^2) : \Leftrightarrow f_i(x^1) \leq f_i(x^2) \\ \forall i = 1, 2, \dots, p, f(x^1), f(x^2) \in \mathbb{R}^p$$

where at least one of the inequalities is strict. A solution for the overall problem is a Pareto-optimal solution:

$$f(\hat{x}) \in \mathbb{R}^p \Leftrightarrow \exists f(\hat{x}) \neq f(\hat{x}) \leq f(\hat{x}) \text{ and } x \in X_0$$

As a generic decision support tool, we can now implement a discrete multi-criteria approach to find an efficient strategy (scenario) that satisfies all the actors and stake holders involved in the water resources management decision processes.

The preferences of decision makers can conveniently be defined in terms of a reference point, that indicates one (arbitrary but preferred) location in the solution space. Normalizing the solution space in terms of achievement or degree of satisfying each of the criteria between nadir and utopia allows us to find the nearest available Pareto solution efficiently by a simple distance calculation.

Since decision and solution space are of relatively high dimensionality, the direct comparison of a larger number of alternatives becomes difficult in cognitive terms. The data sets describing the scenarios can be displayed in simple scattergrams, using a user defined set of criteria for the (normalized) axes. Along these axes, constraints in terms of minimal and maximal acceptable values of the performance variable in question can be set, leading to a screening and reduction of alternatives.

As an implicit reference point, the utopia point can be used. Consequently, and unless the user overrides this default by specifying an explicit reference point, the system always has a solution (the feasible alternative nearest to the reference point) that can be indicated and highlighted on the scattergrams and in a listing of named alternatives.

Satisficing revisited

A naïve second look at the satisficing paradigm will yield some suggestions for the implementation of DSS and their use in a participatory decision making process.

We conceptualise the set of alternatives (existing or to be generated) as described by an attribute vector X_i . The decision maker now expresses aspirations in terms of these criteria. For each, the requirement expressing aspirations can be to:

Minimize or maximize the value of the criterion;
Meet a constraint, i.e., a minimal or maximal allowable value.

In the optimization case (1), there are implicit trade-offs between the objectives, expressed in terms of the criteria implied, when we try to improve more than one at a time, conjunctively. Much of the multi-attribute decision theory literature revolves around how to best elicit and implement these relationships, for example as weights on individual criteria expressing relative importance, or as a reference point defining scaling for all of them simultaneously. However, both the procedure and the underlying concepts are somewhat complex, involved, and not easily used other than with a captive audience of students of decision theory..

In the case of expressing aspiration as a set of constraints, the procedure is simple, intuitively understandable, and lends itself well to a participatory approach:

An initial set of reasonable constraint values are defined in the natural units of the criteria which makes the procedure easy to understand;
A solution or set of solution that meets the criteria is “found” in the set of available alternatives or generated e.g., by simulation modelling;
If the set is empty, the constraints are relaxed – the sequence and degree of relaxation are a reflection of the DM’s preferences, but at the same time an understanding of tradeoffs, possibly the results of a negotiation process between several decision makers with conflicting objectives;
If the set includes more than one solution, the constraints can be tightened in the same interactive and iterative procedure as above, but in the opposite direction.
The procedure ends whenever the decision makers are satisfied.

From a game theoretical point of view (e.g., Gibbons 1997), step (3) is where the transition from a perceived zero-sum game or a version of the prisoners dilemma with dominant strategies with a possibly suboptimal equilibrium to a cooperative game should be introduced. In terms of water use, while allocation for consumptive use may indeed be understood as a zero sum game, total extractions are not. The possibility for recycling and re-use of water clearly shows the potential for a cooperative game approach.

The idea of a cooperative game approach, however, requires the introduction of the appropriate coordination and in fact, exchange mechanisms: without the possibility to trade water in some sense so that the overall benefits of use can be increased together with individual user benefits, this is difficult if not impossible to implement.

This simply requires the institutional structures or market mechanisms to make this level of cooperation and coordination, i.e., truly integrated water resources management possible.

Conflict resolution, rational trade-off, Pareto efficiency

The essential function of the final multi-criteria optimization is conflict resolution.

The different criteria and objectives are competing or conflicting, so a solution always involves a trade-off between criteria and objectives, and thus between stakeholders or interest groups.

This final stage, however, pre-supposes that the alternatives considered are non-dominated or Pareto-optimal or Pareto efficient. Pareto optimality, named after Italian economist Vilfredo Pareto (1906), is a measure of efficiency in multi-criteria and multi-party situations. The concept has wide applicability in economics, game theory, multicriteria optimization, multicriteria decision-making, and the social sciences generally. Multicriteria problems are those in which there are two or more criteria measured in different units ("apples and oranges"), and no agreed-upon conversion factor exists to convert all criteria into a single metric.

Pareto optimality can be defined as follows:

Pareto optimality defines a criterion for optimization problems with multi-criteria objectives (multi-criteria optimization). A state A (a set of object parameters) is said to be Pareto optimal, if there is no other state B dominating the state A with respect to a set of objective functions. A state A dominates a state B , if A is better than B in at least one objective function and not worse with respect to all other objective functions.

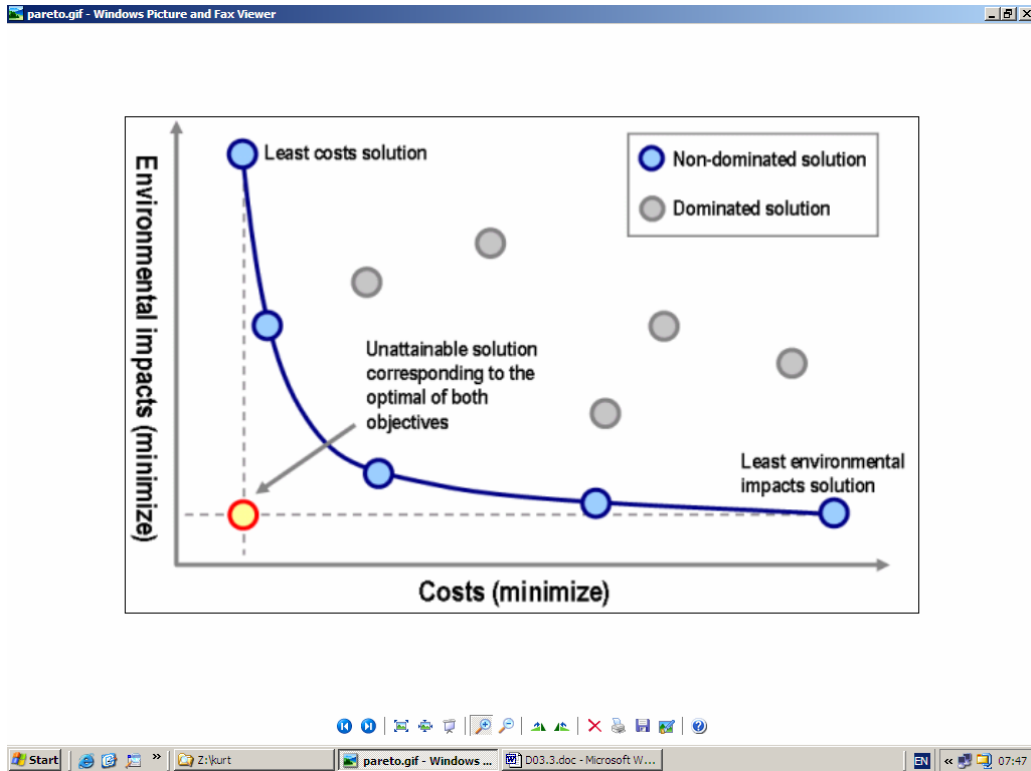
Given a set of alternative allocations and a set of individuals, a movement from one alternative allocation to another that can make at least one individual better off, without making any other individual worse off is called a Pareto improvement or Pareto optimization. An allocation of resources is Pareto efficient or Pareto optimal when no further Pareto improvements can be made.

A situation is Pareto-optimal if by reallocation you cannot make someone better off without making someone else worse off. In Pareto's words: "we will say that the members of a collectivity enjoy maximum ophelimity in a certain position when it is impossible to find a way of moving from that position very slightly in such a manner that the ophelimity enjoyed by each of the individuals of that collectivity increases or decreases. That is to say, any small displacement in departing from that position necessarily has the effect of increasing the ophelimity which certain individuals enjoy, and decreasing that which others enjoy, of being agreeable to some, and disagreeable to others." (Pareto, 1906).

In simple language, a solution can be considered Pareto optimal if there is no other solution that performs at least as well on every criteria and strictly better on at least one criteria. That is, a Pareto-optimal solution cannot be improved upon without hurting at least one of the criteria. Solutions that are Pareto-optimal are also known in various literatures as nondominated, noninferior, or Pareto-efficient. A solution is not Pareto-optimal if one criteria can be improved without degrading any others. These solutions are known as dominated or inferior solutions.

Pareto optimality can be visualized in a scatterplot of solutions (see the figure below). Each criterion (or objective function) is graphed on a separate axis. It is easy to visualize in a problem with only two criteria, but much more difficult with three or more criteria. In a problem with two criteria, both of which are to be minimized (in the OPTIMA baseline scenarios, consider the number of violation of environmental standards versus the costs of wastewater treatment as candidate criteria), Pareto-optimal solutions are those in the scatterplot with no

points down and to the left of them. Dominated solutions are those with at least one point down and to the left of them.



It seems obvious that a rational agent would not consider a solution that is at best equal in most, but worse in at least one of the criteria, compared to all other solutions, or in other terms, that can be improved upon without extra cost. This, however, assumes that the set of criteria chosen is complete and representative, and there are no “hidden agenda” not represented in the formal decision making process. In practice, this is a situation frequently encountered, but easily identified.

And it is worthwhile repeating that the entire methodology is not so much about finding the best solution (as there hardly ever is such a thing undisputed) but to improve the process by which a satisfactory solution for all legitimately involved can be found.

References and selected Bibliography

- Bell, D.E., Keeney, R.L., Raiffa, H. (1977)** *Conflicting Objectives in Decisions*. 442 pp., John Wiley, Chichester.
- Byron, M. (1998)** Satisficing and Optimality. *Ethics* 109, 67-93.
- Christofides, A., Efstratiadis, A. Koutsoyiannis, D., Sargentis, G.-F. and Hadjibiros, K. (2005)** Resolving conflicting objectives in the management of the Plastiras Lake: can we quantify beauty? *Hydrology and Earth System Sciences* (2005) 9: 507-515
- Cohon, J. (1978)** *Multiobjective programming and planning*. Academic Press. London
- Conley, W. (1980)** *Computer Optimization Techniques*. 266 pp., Petrocelli, New York.
- Cougar, J.D. and Knapp, R. (1974)** *Systems Analysis Techniques*. John Wiley & Sons. 1974. ISBN 0-471-17735-0
- Duncombe, W., Johnston, J.M. (1998)** Balancing Conflicting Policy Objectives: The Case of School Finance Reform *Public Administration Review*, Vol. 58, 1998
- Easton, R. (1973)** Complex managerial decision involving multiple objectives. Wiley and Sons.
- Fedra, K. (2004a)** Coastal Zone Resource Management: Tools for a Participatory Planning and Decision Making Process. In: Green, D.R. et al. [eds.]: *Delivering Sustainable Coasts: Connecting Science and Policy*. Proceedings of Littoral 2004, September 2004, Aberdeen, Scotland, UK., Volume 1, 281-286 pp.
- Fedra, K. (2004b)** Water Resources Management in the Coastal Zone: Issues of Sustainability. In: Harmancioglu, N.B., Fisitikoglu, O., Dikilic, Y, and Gul, A. [eds.]: *Water Resources Management: Risks and Challenges for the 21st Century*. Proceedings of the EWRA Symposium, September 2-4, 2004, Izmir, Turkey, Volume I, 23-38 pp.
- Fedra, K. (2002)** GIS and simulation models for Water resources Management: A case study of the Kelantan River, Malaysia. 39-43 pp., *GIS Development*, 6/8.
- Fedra, K. (2000)** *Environmental Decision Support Systems: A conceptual framework and application examples*. Thèse présentée à la Faculté des sciences, de l'Université de Genève pour obtenir le grade de Docteur ès sciences, mention interdisciplinaire. 368 pp., Imprimerie de l'Université de Genève, 2000.
- Fedra, K. (1983)** A Monte Carlo Approach to Estimation and Prediction. In: M.B. Beck and G. van Straten [eds.]: *Uncertainty and Forecasting of Water Quality*, Springer-Verlag, Berlin. pp.259-291.
- Fedra, K., and Jamieson, D.G. (1996)** An object-oriented approach to model integration: a river basin information system example. In: Kovar, K. and Nachtnebel, H.P. [eds.]: *IAHS Publ. no 235*, pp. 669-676.
- Golden, B. L., Harker, P.T., and Wasil. E.A. (1987)** [eds.] *The Analytic Hierarchy Process. Applications and Studies*, Springer, New York.
- Gillet, B.E. (1976)** *Introduction to Operations Research. A computer-oriented algorithmic approach*. 617 pp, MacGraw-Hill, New York.
- Harris, J.W. and Stocker, H. (1998)** *Handbook of Mathematical and Computational Science*. 1028 pp., Springer, Heidelberg.
- Hayashi, K. (1999)** Rethinking weight elicitation for analytic hierarchies; practical implications of the modifications. Proceedings of the Fifth International Symposium on the Analytic Hierarchy Process, Kobe, 194-199.
- Hayashi, K. (1998)** Multicriteria aid for agricultural decisions using preference relations; methodology and application. *Agric. Syst.*, 58 (4), 483-503.
- Heilman, P., Yakowitz, D. S. and Lane, L. J. (1997)** Targeting farms to improve water quality. *Appl. Math. Comput.*, 83, 173-194.
- Hokkanen, J. and Salminen, P. (1997)** ELETRE III and IV decision aids in an environmental

problem. *Journal of Multi-Criteria Analysis*. 6(3): 215-226.

Holmes, W. (1971) An ordinal method of evaluation. *Urban Studies* 9:179-191

Jamieson, D.G. and Fedra, K. (1996) The WaterWare decision-support system for river basin planning: I. Conceptual Design. *Journal of Hydrology*, 177/3-4, pp. 163-175.

Keeney, R. and Raiffa, H. (1976) Decisions with multiple objectives: preferences and value trade-off. Harvard University Press.

Lawrence, P. A. et al. (1997) Using measured data and expert opinion in a multiple objective decision support system for semiarid rangelands. *Trans. ASAE*, 40 (6), 1589-1597.

Loucks, D.P., Stedinger, J.R. and Haith, D.A. (1981) Water resources Systems Planning and Analysis. 559 pp, Prentice Hall, Englewood Cliffs, NJ.

Malczewski, J. and Ogryczak, W. (1997) The multiple criteria location problem; a generalized network model and the set of efficient solutions. *Environment and Planning A*. 27(12):1931-1960.

Massam, B.H. (1988) Multi-criteria decision making (MCDM) techniques in planning. *Progress in Planning*. 30(1):1-84.

Michalewicz, Z. and Fogel, D.B. (1998) How to Solve It: Modern Heuristics. 467 pp, Springer, Berlin.

Mendoza, G.A. (1997) Introduction to Analytic Hierarchy process: Theory and applications to Natural Resources Management. In: *Proceedings of 1997 ACSM/ASPRS Annual Convention*. Vol 4. Resource Technology held in Seattle, Washington on April 7 - 10. 130-139.

Moore, P., & Fitz, C. (1993). Gestalt Theory and Instructional Design.

J. Technical Writing and Communication, 23 (2), 137-157, 1993.

Nijkamp, P., Rietveld, P. and Voogd, H. (1990) Multicriteria Evaluation in Physical Planning North-Holland, Amsterdam.

Pareto, V. (1906) Manual of Political Economy. 1971 translation of 1927 edition, New York: Augustus M. Kelley.

Rehman, T. and Romero, C. (1993) The application from MCDM paradigm to the management of agricultural systems: Some basic considerations. *Agricultural Systems*. 41(3): 239-255.

Richardson, J.S. (2004) Meeting the conflicting objectives of stream conservation and land use through riparian management: another balancing act. Pages 1-6 in G.J. Scrimgeour, G. Eisler, B. McCulloch, U. Silins and M. Monita. [eds.] *Forest-Land-Fish Conference II Ecosystem Stewardship through Collaboration*. Proc. Forest-Land-Fish Conf. II, April 26-28, 2004.

Rios Insua, D. (1990) Sensitivity Analysis in Multiobjective Decision Making. Springer-Verlag, New York, USA.

Romero, C. (1996) decision analysis and environmental economics: An approximation. *European Journal of Operations Research*. 96:81-89.

Roy, B. (1996) Multicriteria Methodology for Decision Aiding. Kluwer Academic Publishers. Dordrecht.

Roy, B. (1991) The outranking approach and the foundations of the ELECTRE methods. *Theory and Decisions*. 31: 49-73.

Rustagi, K. and Bare, B. (1987) Resolving multiple goal conflicts with interactive goal programming. *Can. J. of forest Research*. 17:1401-1407.

Saaty, T.L. (1995) Decision making for leaders: The analytic hierarchy process for decisions in a complex world. RWS Publication, PA. 3rd. Edition.

Simon, H.A. (1969) The Science of the Artificial. MIT Press, Cambridge, MA.

Simon, H.A. (1957) Models of Man. Social and Rational. Wiley, NY.

Szejnwald Brown, H., Derr, P., Ortwin Renn, O., and White, A.L. (1993) Corporate Environmentalism in a Global Economy: Societal Values in International Technology Transfer, (Connecticut: Quorum Books, 1993), 245 pp.

- Tiwari, D. N., Loof, R. and Paudyal, G. N. (1999)** Environmental-economic decision-making in lowland irrigated agriculture using multi-criteria analysis techniques. *Agric. Syst.*, 60 (1), 99-112.
- Vargas, L.G. and Zahedi, F. (1993)** [Eds]. *Analytic Hierarchy Process. Special Issue. Mathematical and Computer Modeling.* 17(4-5): 1-195.
- Vincke, P. (1999)** Outranking approach. In: *Multicriteria decision making*, Gal, T., Stewart, T. J. & Hanne, T. [eds.], Kluwer Academic Publishers, Dordrecht, 11-1- 11-29.
- Vincke, P. (1989)** *Multi-criteria Decision Aid.* Wiley. London
- Voogd, H. (1983)** *Multicriteria evaluation for urban and regional planning.* Academic Press. London.
- Wertheimer, W. (1924)** Über Gestalttheorie [an address before the Kant Society, Berlin, '7th December, 1924], Erlangen, 1925. In the translation by Willis D. Ellis published in his "Source Book of Gestalt Psychology," New York: Harcourt, Brace and Co, 1938.
- Wierzbicki, A. (1998)** Reference Point Methods in Vector Optimization and Decision Support. IR-98-017, 43 pp ; International Institute for Applied Systems Analysis, Laxenburg, Austria.
- Yakowitz, D. S., Lane, L. J. and Szidarovszky, F. (1993)** Multi-attribute decision making; dominance with respect to an importance order of the attributes. *Appl. Math. Comput.*, 54, 167-181.