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Multi-Agent Systems optimization for distributed watershed management

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Abstract: Water systems are characterized by the presence of many and often conflicting interests as well as distributed independent decision-makers. The traditional centralized approach to water management, as described in much of water resources literature, should be therefore reconsidered in the light of a more realistic, decentralized representation of the decision-making structure in order to provide effective solutions for policy making. In this paper we use Multi-Agent Systems (MAS) to analyse the role of a hypothetical watershed authority, which has to deliver a management plan at the watershed level starting from an uncoordinated situation. MAS provide powerful modeling and analytical tools to tackle this problem as they naturally allow to represent a set of heterogeneous and self-interested agents (e.g., the operator of a reservoir or a diversion dam, or an environmental organization) acting in a distributed decision-making process at the individual water user or stakeholder level. MAS have been widely explored in the water resources field, however most of these works focused on the use of agents as modeling tools, whereas only few considered them as optimization units. In this paper we adopt MAS within both a Distributed Constraint Satisfaction and Distributed Constraint Optimization framework to characterize different strategies between the two extremes of a centralized and a fully distributed management. The proposed approaches are demonstrated on a steady state hypothetical watershed management problem, involving several active human agents and reactive ecological agents. Results show that the imposition of normative constraints on agents' decisions through a mechanism design strategy allows the watershed authority to effectively design an efficient and socially acceptable distributed watershed management.

Keywords: Multi-Agent Systems; Watershed management; Distributed Constraint Satisfaction/Optimization; Mechanism design

1 INTRODUCTION

The presence of multiple, distributed and institutionally-independent decision-makers (DMs) is challenging the traditional centralized approach to water resources management as underlying much of the sector literature (e.g., Soncini-Sessa et al. [2007] and references therein). This approach usually assumes a top-down decision-making process, complete information exchange, and perfect economic efficiency [Yang et al., 2009]. These assumptions are often unsuitable in real world contexts and the centralized management, though interesting from a conceptual point of view, turns out to be of low practical interest. Conversely, a decentralized bottom-up approach would allow to represent the institutional framework more realistically, suggesting solutions that might be politically feasible. Yet, mathematical and technological tools to develop this methodology are nearly undeveloped and, therefore, the applicability of such an approach has been limited so far.

Multi-Agent Systems (MAS) provide a potentially interesting framework to model multiple and self-interested DMs acting in a distributed decision-making process at the agent (DM and/or stakeholder) level. In fact, watersheds can be naturally modeled as MAS, where each real-world actor is represented one-to-one by a computer agent, defined as a computer system situated in some environment and capable of autonomous actions to meet its design objectives [Wooldridge, 2009]. MAS approaches have been explored in environmental systems from the late 1990s [Bousquet and Le Page, 2004] and, recently, they have been exploited in several research contexts (e.g., Athanasiadis et al. [2009]; Worrapimphong et al. [2010]; Ioannou et al. [2011]; Schreinemachers and Berger [2011]). However, despite their wide application, the use of MAS for the analysis and design of water system alternative operations has not been fully explored [Yang et al., 2009]. Moreover, agent technology has been seldom adopted in environmental studies: only agent-based modeling [Bonabeau, 2002] and simulation [Bousquet and Le Page, 2004] registered a wide diffusion, but there is still room for exploiting agent tools and techniques [Athanasiadis, 2005], particularly in problems that can benefit from the capability of the agents of optimizing their behaviour.

The aim of this paper is to develop a MAS optimization-based approach for designing distributed watershed management by the viewpoint of a water authority in charge of coordinating multiple independent decision-makers. In our work, starting from the inefficient configuration of totally uncoordinated and self-interested agents, we develop a *mechanism design* [Maskin, 2008] strategy by imposing a set of soft (normative) constraints on the agents' decisions that should drive the solution towards a more efficient situation. It is worth noting that the maximum efficiency can be obtained with a centralized management, where the agents are completely constrained and act according to the decisions imposed by the centralized authority. The watershed management problem is therefore formulated as a distributed constrained problem, which can be effectively managed through agent-based methods like those for Distributed Constraint Satisfaction Problems (DCSP, see Yokoo and Hirayama [2000]) and Distributed Constraint Optimization Problems (DCOP, see Modi et al. [2005]), which moreover guarantee global solution quality operating efficiently using only local communicaton.

The paper is organized as follows: the next section describes the methodology, while Section 3 presents a description of the test case study. Results are reported in Section 4 and final remarks, along with issues for further research, are presented in the last section.

2 METHODS AND TOOLS

To introduce the proposed DCSP-DCOP methods for the agent-based optimization, let's consider the following centralized k-objective optimization problem

$$\max_{\mathbf{x}} \mathbf{f}(\mathbf{x}) = (f_1(\mathbf{x}), f_2(\mathbf{x}), \ldots, f_k(\mathbf{x})) \tag{1a}$$

s.t.

$$c_1(\mathbf{x}), c_2(\mathbf{x}), \ldots, c_r(\mathbf{x}) \leq 0 \tag{1b}$$

$$\mathbf{x} \in \mathcal{D} \tag{1c}$$

where $\mathbf{x} \in \mathbb{R}^n$ is the decision vector, $\mathbf{f}(\mathbf{x})$ is the k-dimensional objective vector, $f_i(\mathbf{x})$ is the i-th objective to be maximized, and eq. (1b) defines constraints on the values of $\mathbf{x}$, whose domain is $\mathcal{D}$ (also called decision space). Generally, Problem (1) is solved in a centralized way, thus computing a set of Pareto-efficient solutions. However, a centralized solution requires a cooperative framework where some agents (typically, the upstream water users) agree on decreasing their benefit to improve the benefit of others users: a condition that is hardly pursuable in most of real-world contexts. More commonly, each DM acts considering his objective only and produces sub-optimal boundary conditions for the others. A MAS framework permits to model a set of non-cooperative DMs, thus reproducing more realistically the actual individualistic interaction. Then, given the ideal centralized solution and the real independent one, it is possible to reduce agents independency in order to push the result towards an approximation of the centralized solution by developing a *mechanism design* approach. The main idea of mechanism design [Baliga and Maskin, 2003; Maskin, 2008] is the following: knowing what we would like to obtain, since the outcome depends on many individualistic agents, define a procedure for obtaining a good solution for the entire system, i.e., a *social choice*. Hence, the watershed authority may define a suitable set of normative constraints to condition agents decisions. In addition to providing a suitable modeling framework for this class of problems, MAS provide also effective methods for solving distributed constrained problems. In particular, Problem (1) can be considered as a Distributed Constraint Satisfaction Problem (DCSP) or as a Distributed Constraint Optimization Problem (DCOP). Under this perspective, each decision variable x_i is associated to one agent, which determines its value, and there exists a set of hard (physical) and, possibly, soft (normative) constraints among the values of the distributed agents variables.

Formally, a DCOP [Modi et al., 2005] consists of n variables, $\mathbf{x} = [x_1, x_2, \ldots, x_n]$, each assigned to an agent, where the values of the variables are taken from finite, discrete domains $\mathcal{D}_1, \mathcal{D}_2, \ldots, \mathcal{D}_n$, and of a number of valued constraints over the values of these variables. The goal is to choose values for the variables minimizing a given objective function, described as a weighted sum over a set of cost functions or valued constraints. The definition of a DCSP is analogous except that the constraints in DCSP are boolean and can be only satisfied or unsatisfied, and so there are not solutions with a certain degree of quality or cost. Hence, while a DCOP is an optimization problem, a DCSP is a feasibility problem. Among the set of available algorithms for solving DCSP and DCOP (see Yokoo and Hirayama [2000] and references therein), the Asynchronous Distributed OPTimization (ADOPT) algorithm by Modi et al. [2005] is applied in this work. ADOPT provides theoretical guarantees on the global solution quality, while it operates both efficiently and asynchronously using only local communication, i.e., each agent does not send messages to every other agent but only to neighboring agents (two agents are *neighbors* if they share a constraint between their associated variables).

The result obtained by adopting a DCSP formulation is a feasible assignment of the variable values, meaning that all the constraints (physical and normative) have to be satisfied. However, this condition may be too restrictive as in some situations limited violations of normative constraints may be tolerated or even unavoidable (e.g., in extreme drought periods it is possible that the water availability is insufficient to satisfy a minimum water demand). The adoption of a DCOP formulation provides more flexibility in dealing with normative constraints, because the result minimizes the weighted sum of constraints violations: the satisfaction of physical constraints is guaranteed by assigning them an infinite weight, while normative constraints may be violated if there are no other feasible solutions. Summarizing, in this paper the ideal centralized solution is compared to three different distributed alternatives: i) an *independent* solution where each DM acts considering his objective only; ii) a DCSP solution where the agents try to maximize their objective functions, but the assignment of decision variables values has to be feasible, i.e. all the constraints imposed on the problem have to be satisfied; iii) a DCOP solution where the agents decisions, which aim to optimize agents objective functions, are only influenced by normative constraints that may be violated; however, it is guaranteed that the solution minimizes the sum of constraints violation.

3 CASE STUDY DESCRIPTION

The proposed MAS-based optimization approach is tested on the hypothetical water system first presented in Yang et al. [2009]. The system, see Figure 1, is composed by a Y-shaped river with one mainstream and one tributary. The mainstream provides water to a city for municipal and industrial uses and, then, the river is dammed for hydropower energy production. Two agricultural districts divert water for irrigation from both the lower mainstream and the tributary. Moreover, there exist two ecological points of interest (POI) on the two rivers, just below the irrigation diversions, that are identified as primary fish habitats. Six agents represent the different water-related interests:

A_1 municipal water supply to the city;

A_2 hydropower production;

A_3 irrigation water supply to the agricultural district on the tributary;

A_4 irrigation water supply to the agricultural district on the lower mainstream;

A_5 ecological preservation in the tributary POI;

A_6 ecological preservation in the mainstream.

Agents A_1-A_2-A_3-A_4 are *active agents*, who really make decisions, while agents A_5-A_6 are *reactive agents*, who do not make decisions but represent the ecological interests. Each agent has an associated quadratic concave objective function, which preserves the nonlinear characteristics of a real objective: $f_i = a_i x_i^2 + b_i x_i + c_i$ (the values of the parameters are reported in Table 1).
Assuming for simplicity a non-dynamic situation (all the variables, both flows and reservoir storage, are expressed as volumes [L^3]), the watershed optimization problem, subject to physical constraints, can be formulated as:

$$\max_{x_1} f_1(x_1) \quad s.t. \quad x_1 \leq Q_1 \tag{2a}$$

$$\max_{x_2} f_2(x_2) \quad s.t. \quad x_2 \leq S + Q_1 - x_1 \tag{2b}$$

$$\max_{x_3} f_3(x_3) \quad s.t. \quad x_3 \leq Q_2 \tag{2c}$$

$$\max_{x_4} f_4(x_4) \quad s.t. \quad x_4 \leq x_2 + Q_2 - x_3 \tag{2d}$$

$$\begin{aligned} x_5 &= Q_2 - x_3 \\ x_6 &= x_2 + x_5 \end{aligned} \tag{2e}$$

where Q_1 is the mainstream inflow, Q_2 the tributary inflow, and S the reservoir storage. Three hydrological scenarios are defined: a *high-flow* scenario ($Q_1 = 80$; $Q_2 = 40$; $S = 10$), where the available water allows each active agent to achieve its optimal solution; a *medium-flow* scenario ($Q_1 = 40$; $Q_2 = 20$; $S = 8$), and a *low-flow* scenario ($Q_1 = 15$; $Q_2 = 8$; $S = 3$), where the water supply is insufficient to satisfy all the agents demands, thus producing upstream-downstream water sharing interactions.
In order to improve the independent solution of the problem (especially in the medium- and low-flow scenarios), in which upstream agents overuse the available water and downstream agents suffer water shortage, we can add the following set of soft constraints to Problem (2) assuming they represent normative constraints imposed by the watershed authority:

$$
\begin{aligned}
&\alpha_1 - x_1 \leq 0 \\
&\alpha_2 - Q_1 + x_1 \leq 0 \\
&\alpha_3 - x_3 \leq 0 \\
&\alpha_5 - Q_2 + x_3 \leq 0 \\
&\alpha_4 - x_4 \leq 0 \\
&\alpha_6 - x_2 - x_5 + x_4 \leq 0
\end{aligned}
\tag{3}
$$

where α_1 is the minimum water demand of the city, α_2 is the minimum flow requirement for hydropower production, α_3 and α_4 are the minimum water demands of the farmers on the tributary and on the lower mainstream, respectively, α_5 and α_6 are the flow requirements for the ecological POI on the tributary and on the lower mainstream, respectively. The values of the parameters α are reported in Table 1. It is worth noting that the physical constraints in Problem (2) are obviously non-violable, while the normative constraints (eqs. (3)) may be violated by the self-interested agents.

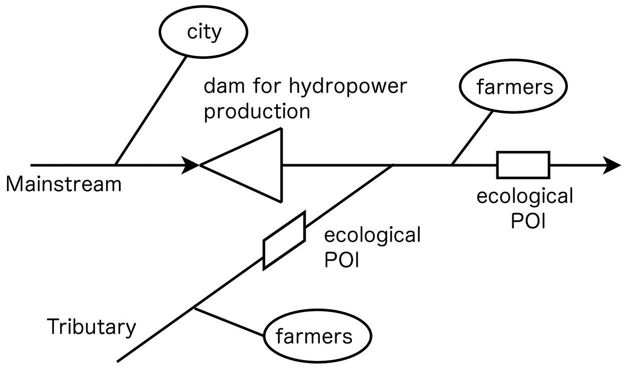


Figure 1: Schematic map of the system.

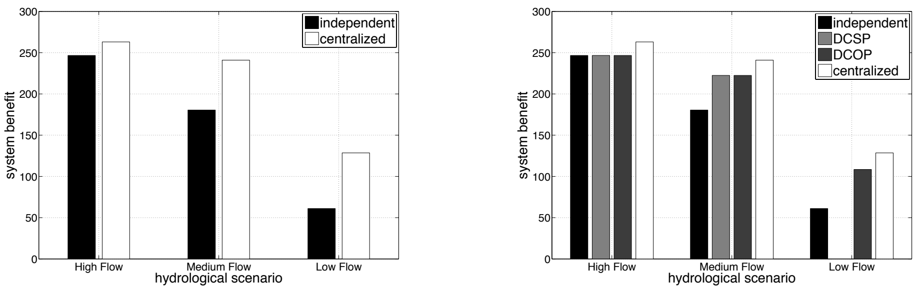
Table 1: Values of parameters defining agents objective functions and constraints [Yang et al., 2009]. Coefficients a_i, b_i and c_i are dimensionless, parameters α_i are expressed in [L^3].

Parameter	Value	Parameter	Value	Parameter	Value	Parameter	Value
a_1	-0.20	b_1	6	c_1	-5	α_1	12
a_2	-0.06	b_2	2.5	c_2	0	α_2	10
a_3	-0.13	b_3	6	c_3	-6	α_3	8
a_4	-0.15	b_4	7.6	c_4	-15	α_4	15
a_5	-0.29	b_5	6.28	c_5	-3	α_5	6
a_6	-0.056	b_6	3.74	c_6	-23	α_6	10

4 RESULTS

In order to test the proposed approach for the design of a MAS-based watershed management, first the centralized solution to Problem (2) was computed for every hydrological

scenario. It is assumed that the social choice is to maximize the system benefit through a compromise solution among the six water-related interests, considering explicitly also the ecological objectives in the centralized optimization and assigning the same weight to each agent. However, this is an ideal solution representing an unfeasible reference benchmark in real world contexts. The real solution, instead, is obtained assuming completely independent and non-cooperative agents, who decide by optimizing their objective function only. The comparison between the system benefit (i.e., the sum of the benefits of the six agents) for these two extreme solutions is represented in Figure 2(a). Not surprisingly, the centralized solution produces higher benefits in all the considered scenarios, and the gap between the two solutions increases when water availability decreases.
Given these results, the mechanism design approach performed by the watershed authority is modeled by adding the set of constraints defined in eqs. (3) to Problem (2), in order to push the independent solution towards the centralized one. Figure 2(b) shows a graphical comparison of the system benefit for the centralized and the independent solutions with the results obtained solving the new constrained problem with DCSP- and DCOP-based approaches. In the high-flow scenario, the independent, DCSP and DCOP solutions are all equivalent because each active agent is able to maximize its objective function; the centralized solution outperforms the distributed ones due to the explicit optimization of the ecological objective functions. In the medium-flow scenario, the DCSP and DCOP solutions are equivalent because it is possible to find out a solution that does not violate any normative constraint, and they both improve the independent solution. In the low-flow scenario, the DCSP solution does not exist because it is impossible to satisfy all the constraints; the DCOP solution, instead, largely outperforms the independent one. More details are provided in Figure 3, where the benefit of each agent is represented. It is worth noting that the centralized solution, which is globally better than all the others in the high-flow scenario, is able to effectively exploit the trade-offs relationships among the different agents objectives: the benefits of A_2, A_3 and A_4 are slightly decreased with respect to the independent solution to generate more significant increase of A_5 and A_6 benefits. The medium-flow scenario provides the most interesting results, as it emphasizes the improvement in the ecological agents benefits in the DCSP and DCOP solutions (which are equivalent in this scenario) with respect to the independent solution. Finally, in the low-flow scenario, where even the centralized solution is not able to guarantee a positive benefit to the ecological agents, the DCOP solution (the DCSP one does not exist) is able to balance at least the benefits of the active agents avoiding the upstream overuse of water (e.g., see the differences between the couples of upstream-downstream agents (A_1,A_2) and (A_3,A_4)).



(a)

(b)

Figure 2: Graphical comparison between the ideal centralized solution and the real independent one (panel a). Comparison of system benefits for centralized, independent and DCSP/DCOP solutions (panel b).

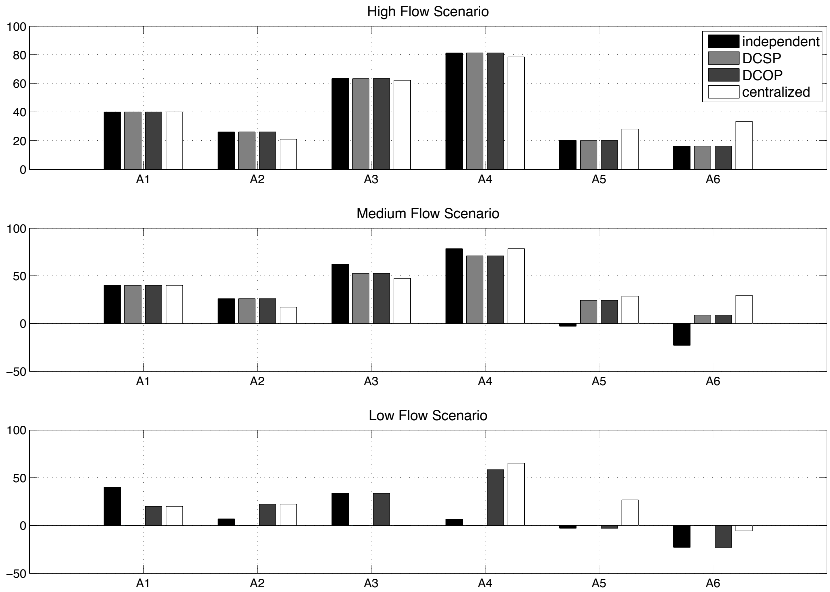


Figure 3: Agents benefits in the three considered scenarios.

5 CONCLUSIONS

In this paper, we presented a Multi-Agent Systems approach to develop a mechanism design strategy for distributed watershed management in large-scale water systems characterized by multiple independent decision-makers. This approach is demonstrated on a hypothetical non-dynamic problem, characterized by the presence of several human and ecological agents.

Results show that, between the two extremes of a centralized and a completely independent management, there exists the possibility for designing intermediate distributed solutions that are more efficient than the independent one and more realistic and politically feasible than the centralized management. The proposed DCSP- and DCOP-based approaches allow the watershed authority to impose normative constraints on the agents decisions in order to move the solution towards a more efficient watershed management. The ideal centralized solution remains the most efficient alternative (i.e., it produces the highest system benefit), but the improvement of the DCSP/DCOP solutions with respect to the independent management is fairly significant.

Further research will concentrate on the analysis of the computational requirements of the proposed methods (e.g., measuring the number of exchanged messages) assessing their scalability with an increasing number of agents. Other research efforts will regard the extension of the present study on a dynamic water system through the development of a DCOP Model Predictive Control scheme and its application on a real-world case study.

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