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Multi-Agent System Approach for an Integrated Urban Wastewater Management

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Abstract— The integrated management of Urban Wastewater Systems (UWS) encloses characteristics of complex systems with dynamic processes. The UWS is composed by several heterogeneous and interconnected elements that as a whole exhibit one or more properties not obvious from the properties of the individual parts. Moreover, these elements interact between them as well as with the environment, varying its state.

In order to represent these abovementioned characteristics we suggest to abstract and conceptualize the UWS as a Multi-Agent System. Agents can interact between them and this makes feasible an integrated management of the UWS in order to ensure the Wastewater Treatment Plant efficiency (i.e. to avoid overloads) and to protect the water quality in the river. We propose the development of the Multi-Agent System by using the Gaia methodology. Finally, we propose to deal with the system requirements using a combinatorial optimization process.

***Index Terms*— Agents Paradigm Application, Multi-Agent System, Optimization Process, Urban Wastewater Management.**

I. Introduction

Several authors deal with the integrated management approach of water and wastewater resources [1]-[6]. The integrated management of water resources at the river basin scale implies to go beyond the individual management of the elements in order to take into account all the elements in the river basin, since they are interconnected and their actions affect each other. So, it includes an integrated management of infrastructures and a combined approach of pollution between the effluent quality and the ecological state of the river.

The most important elements of the Urban Wastewater System (UWS) are the sewer system, the Wastewater Treatment Plant (WWTP) and the receiving media (i.e. the river) (Fig. 1). These components perform the most important functions within the overall system. That is, the transport of rainfall and wastewater from the sources to some treatment destination and, after the treatment, the reception of the treated wastewater by the receiving media.

When the capacity of the WWTP is surpassed, several overflows arrived without treatment to the river. Moreover, in industrialized urban areas, industries are an important source of pollutants, which are very variable in quantity and quality of their composition. Consequently, WWTP may receive more flow or more pollutants' load that the one they are capable to manage, reducing their efficiency and affecting, at the end, the quality of the water in the receiving media.

Analyzing the characteristics of the UWS we realize that it is a distributed system with many changeable values. This complexity suggests the feasibility of the agent's paradigm to model the UWS [7]-[9]. Therefore, the UWS may be abstracted as a computational organization consisting of some intertwined roles and into a static organizational structure with an accessible environment by sensors of measurement. As a result, it is feasible to model the UWS as a Multi-Agent System (MAS) composed by heterogeneous and autonomous agents that have a common goal as a whole.

We propose to develop the MAS using the Gaia methodology [10], [11].

Firstly, during the analysis phase, we identify the basic skills that are required by the system organization to achieve its goals. We capture the dependencies and relationships between the various roles in the MAS.

Secondly, during the design phase, we identify the appropriate organizational structure, including topology and control regime. It is also possible to label any existent modular organizational structure in order to help the designer. During the completion of the role and interaction models together with the definition of all activities in which a role would be involved, we identified a particular complex activity between the sewer system and the WWTP. This activity corresponds to the discharge of industrial wastewater. We describe this activity as a combinatorial optimization process.

II. MAS proposal

The modelling of the UWS in terms of MAS is based on the fact that we assume there is one retention tank for each component of the sewer system.

A. Agents

We propose two different types of agents in the MAS. The first one corresponds to the agents directly associated with

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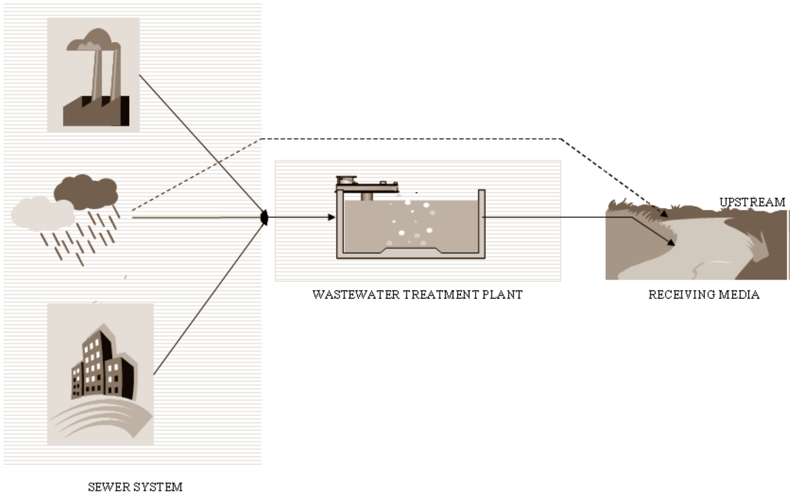

Figure 1. Components of the Urban Wastewater System

measurement sensors. In this group we have the following agents: Household, Rainfall, Industry, WWTP and Receiving Media Agents. The second type corresponds to the agents indirectly associated with measurement sensors. In this group we have identified the Coordinating Agent and the Basin Council Agent.

Measurement sensors make feasible the observation of the environment and they provide the input data of agents. Sensorial inputs correspond to: Volume (V), Total Suspended Solids (TSS), Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Total Nitrogen (TN), Kjeldahl Nitrogen (TKN), Ammonia (N- NH_4^+) and Total Phosphorous (TP).

Each agent of the first group supplies data, corresponding to the state of its particular world, to the agents of the second group with who they have communication. The agents (Coordinating and Basin Council) collect the information about the individual states of the world and calculate the state of its subsystem's world in relation to the whole system.

Concretely, the Coordinating Agent receives data from Household Agent, Rainfall Agent, Industry Agents, WWTP Agent and from the Basin Council Agent. If the state of the receiving media requires more strictly constraints, the Coordinating Agent includes them (as data inputs). Then, it determines the state of the sewer system related to WWTP state, and it builds a decision about the best action to take (see Fig. 2 concerning the Coordinating Agent). It sends these data to Household, Rainfall and Industry Agents. These agents proceed by incorporating these data in their internal world and finally, they decide the execution of their actions.

In fact, the Coordinating Agent takes decisions related to avoid the WWTP overload capacity and to ensure water quality.

On the other hand, the Basin Council Agent receives data from different river sections and takes the final decision with regard to each fluvial section

B. *Communications*

The acquaintances between the agents explain the possible communication paths between the agents. As follows:

1) Basin Council with Household, Rainfall, Coordinating and Receiving Media.
2) Receiving Media with WWTP and Basin Council.
3) WWTP with Coordinating and Receiving Media.
4) Household with Coordinating and Basin Council.
5) Rainfall with Coordinating and Basin Council.
6) Industries with Coordinating.
7) Coordinating with Household, Rainfall, Industries, WWTP and Basin Council.

These communications are necessary in order to ensure that each agent have all data needed to take a good decision in the decision system (see Fig. 3). The timing for the Receiving Media, WWTP, Coordinating, Household, Rainfall and Industry Agents communications works in the same way as indicated in steps 4, 5 and 6 of Section II.D.

The acquaintances are accurately explained into the communication protocols between the agent roles (see a protocol example corresponding to Rainfall discharge in Fig. 4).

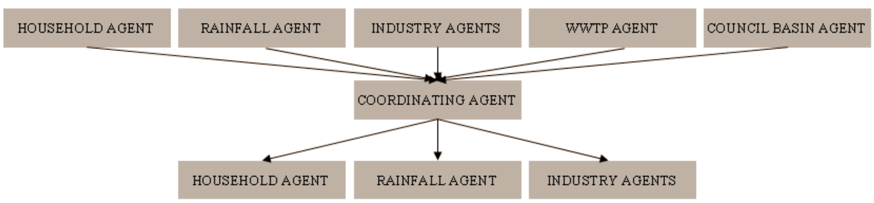

Figure 2. Input and output data of the Coordinating Agent

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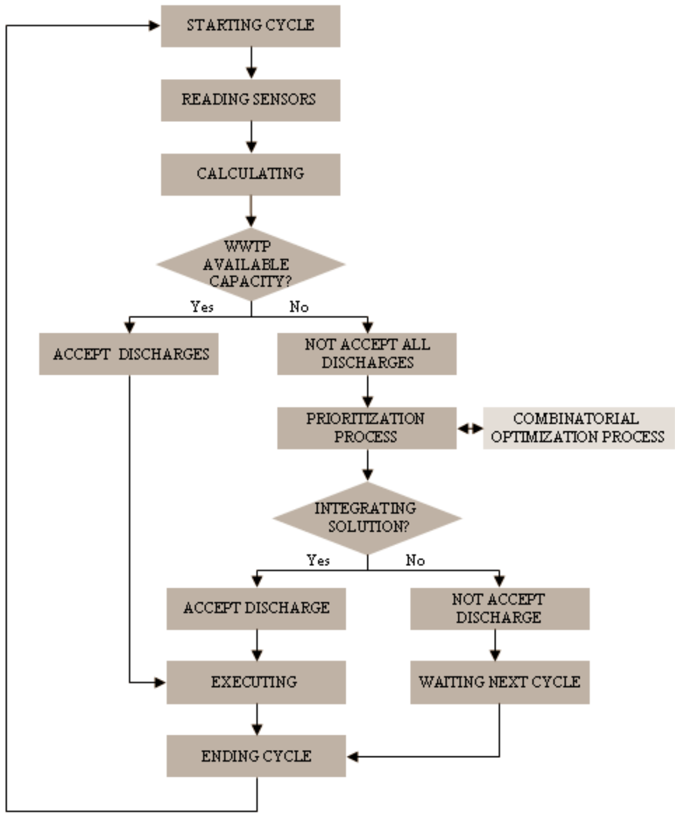

Figure 3. Decision system cycle for discharging wastewaters

C. Decision module for wastewater discharges.

Fig. 3 presents the schema of the decision cycle for discharging wastewaters. At the beginning, the Coordinating Agent accepts to the system the wastewater discharges from household and rainfall. Previously, if the water runoffs from extreme rainfall events are excessively, the Rainfall Agent takes the decision to send these white waters directly to the river.

Then, it calculates and compares volume and pollutants loads in the industrial retention tanks against the WWTP availability. According to this, it decides if it is or it is not feasible to accept all the discharges. If it is not feasible to accept all discharges because the WWTP do not have enough capacity, the cycle runs to a key process. This includes a prioritization of industrial wastewater discharges in which the Coordinating Agent can decide which discharges are going to be accepted regarding constraints in volume and pollutants load.

Notice that in order to have a satisfactory performance of the system; it is necessary to have all decision functions with its safety variables described. These are included in the safety responsibilities of roles. Table I contains some of them for the proposed MAS.

Protocol name: Rainfall discharge to WWTP network.		
Initiator: Rainfall transport from retention tank to WWTP.	**Answering**: Coordination between rainfall discharge and WWTP availability.	**Input**: Wastewater characteristics in retention tank.
Description: It is in charge of discharging the rainfall in retention tanks to WWTP network. Moreover, its sensors do measure of volume and pollutants load		**Output**: Volume and pollutants load to WWTP.

Figure 4. Protocol example describing the communication between two agent roles

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Table I. Safety variables related to the functions in the system.

Agent	Roles	Safety variables for the functions of system
Household	Collect and transport household wastewaters to the WWTP.	Maximum values for volume and pollutants loads, settled by the Council Basin Agent as a function of demography.
Rainfall	Collect and transport of rainfall to the retention tank. Rainfall transport from retention tank to the WWTP or to the receiving media.	Maximum admissible level in the rainfall retention tank. Maximum admissible volume and pollutant loads for rainfall in WWTP inflow.
Industry	Collect and transport effluents to the industrial retention tanks. Effluents discharge from the retention tank to the WWTP.	Maximum admissible level in industrial retention tanks. Maximum admissible volume and pollutant loads for effluents of industrial wastewaters, settled by the Coordinating Agent.
Coordinating	Coordination of wastewater discharges to the WWTP. Prioritize industrial wastewaters discharge to the WWTP. Temporary limitation of parameters in the WWTP inflow.	Maximum admissible volume and pollutant loads for the WWTP inflow, prefixed by the WWTP Agent as a function of WWTP availability related to its saturation degree.
WWTP	Wastewater treatment. Temporary limitation of parameters in the WWTP inflow. Discharge of treated wastewater.	Maximum admissible volume and pollutant loads for its inflow, settled as a function of its capacity and its saturation degree. Maximum admissible volume and pollutant loads for its outflow, settled as a function of the discharge requirements.
Receiving Media	Immission of treated wastewater. Inspection of water quality in the receiving media. Temporary limitation of parameters in WWTP discharges.	Maximum admissible volume and pollutants load for its outflow related to the discharge requirements, settled by Council Basin Agent as a function of upstream water quality.
Council Basin	Coordinate river basin sections. Coordinate maximum values established for sewage system and WWTP. Temporary limitation of parameters in the WWTP inflow.	Maximum admissible volume and pollutant loads for the water in the river basin, settled as a function of characteristics to protect the water quality in the river basin.

D. *Simulation of system communications*

The MAS has been simulated using data from a case study presented in Table II and using the Repast platform [12], [13]. The communications have been programmed in Java language.

The data corresponds to a hypothetical scenario composed by a population, some temporal rainfall events, industries, one WWTP and the receiving media.

The execution of the system in real time requires the development of the following steps:

1) Input of data (from data bases corresponding to sensor measures).
2) Comparison of input data (values) with the equivalent limit values settled.
3) Generation of graphs and visualization of system's state.
4) Execution of the "sending data messages" task to the Coordinating Agent. Initiator agents send data messages one after the order as follows: Receiving Media, WWTP, Household, Rainfall and finally Industry Agents.
5) Execution of Coordinating Agent functions: establishes restrictions, coordinates Household and Rainfall and prioritizes Industrial discharges (among the several Industrial Agents that 'want' to discharge).
   In this cycle execution the prioritization is developed by normalization as a function of the discharged volume of each agent. The timing is a virtual time, a-dimensional, a unit of time in the overall cycle.
6) Execution of sending data messages to Industry, Rainfall, Household and WWTP Agent (Initiator: Coordinating Agent).
7) Graphs generation and visualization of the fill/empty tanks and WWTP's input profiles.

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Table II. Description and data of the case study

WWTP: 11600 m^3/day
Hydraulic retention time of WWTP: 1 day
Population: 50000 inhabitants
Number of cycles: 2/day
Safety values Household: 10440 m^3/day, Rainfall: 10440 m^3/day, Industries: 8120 m^3/day
Industries 1: working 5 days/ week and 8 hours/day (slaughterhouse) 4: working 7 days/week and 24 hours/day (paper packing)
2: working 6 days/week and 16 hours/day (dairy) 5: working 7 days/week and 24 hours/day (textile)
3: working 5 days/week and 16 hours/ day (vegetables mixture) 6: working 7 days/week and 24 hours/day (manufacturing)

Input data corresponding of sensor measures (m^3) in retention tanks

Day		Volumes in retention tanks of Industries						Household	Rainfall
		1	2	3	4	5	6		
1	11 am	1850	45	75	454	155	190	4470	0
1	10 pm	350	145	175	385	130	160	2530	0
2	11 am	1790	50	60	454	155	190	4270	760
2	10 pm	410	145	190	385	130	160	2195	1881
3	11 am	1910	47	75	454	155	190	4530	1139
3	10 pm	300	150	180	385	130	160	2120	1540
4	11 am	1690	52	75	454	155	190	4238	980
4	10 pm	475	149	175	385	130	160	2800	1050
5	11 am	1750	56	75	454	155	190	5091	0
5	10 pm	400	155	175	385	130	160	2126	0
6	11 am	0	49	0	454	155	190	4205	0
6	10 pm	0	150	0	385	130	160	2085	0
7	11 am	0	0	0	454	155	190	3980	0
7	10 pm	0	0	0	385	130	160	1721	0

Fig. 5 presents a screenshot showing the kind of results obtained. The thick line with dots in the main centred graph represents the inflow to the WWTP. It can be observed that it remains constant thanks to the Coordinating Agent function. Its function consists on preventing WWTP overflows by considering the WWTP capacity thresholds. The fluctuating line (thick line with crosses) represents the evolution of the retention tanks level, corresponding to industrial wastewaters as a whole.

In the left side, it is represented the state of the retention tank for each industry and in the small graphs, the evolution of the industries' outflow.

The Fig. 5 offers a good solution related to the discharged volume.

Unfortunately, we have not obtained the best expected solution by using the proposed normalization process of discharges when we consider the pollutant loads. Therefore, we suggest using a new approach for the prioritization process as a combinatorial optimization process [2], [14] to solve this problem.

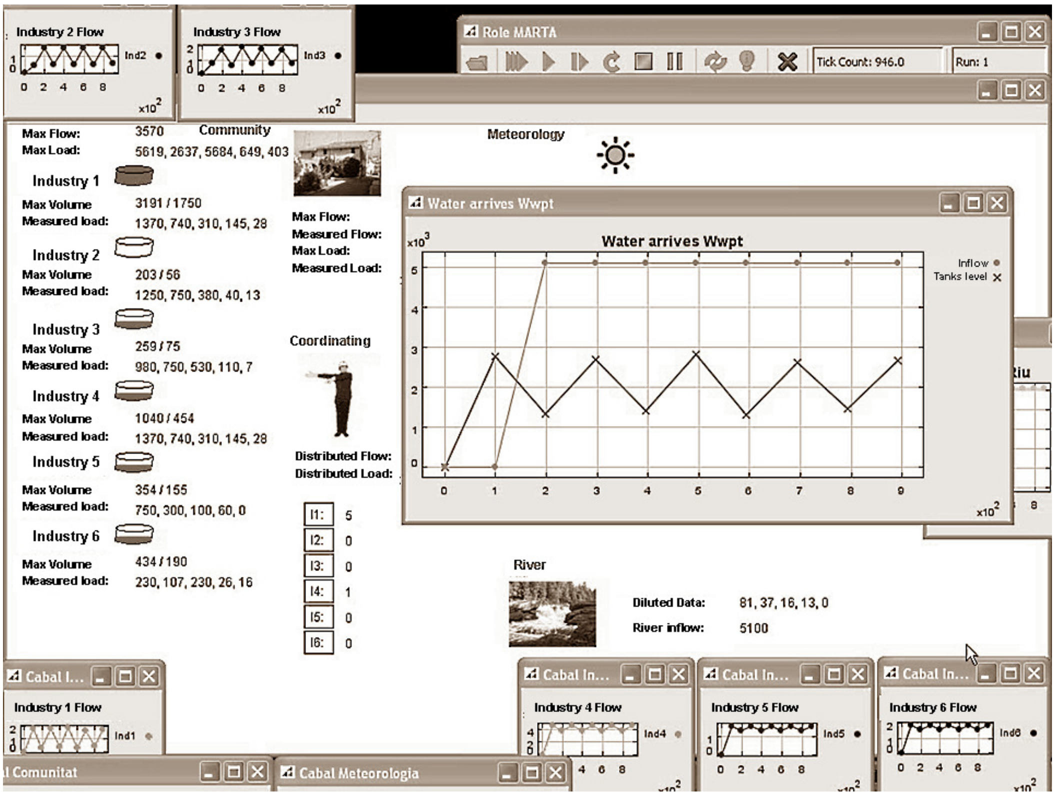

Figure 5. Simulation of agent communications using the Repast platform

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To deal with this process requires metaheuristic information associated to the problem. By building and using a metaheuristic equation it may be feasible to obtain a solution that maximizes the wastewaters discharge for the required constraints in volume and pollutants load.

Attending the pollutants composition in each retention tank for each industrial wastewater, the maximization procedure could be developed by two different approaches:

1) One objective function related to environmental characteristics that integrates all considered parameters: volume and pollutants loads. This problem is constrained by the WWTP availability in volume and pollutants loads (multiple constraints).
2) One objective function related to the economic global cost which depends on the discharged volumes, the pollutants loads and their costs. This approach is constrained in the same way that the first one. In this case, the maximization's cost should mean to approximate the limit availability volume and pollutants loads in feasible discharges.

III. Conclusions

The first conclusions about the behaviour of the proposed MAS can be described as follows:

1) The representation and performance of agent communications are feasible by the use of MAS.
2) In order to respect the constraints of the system in each cycle, the decisions taken by the Coordinating Agent constitute a key point in the overall system decisions.
3) To get a regular inflow (also in pollutant loads), when it is not feasible to accept all industrial wastewater discharges, depends on the prioritization process executed by the Coordinating Agent.
4) The prioritization process requires a method capable to find the best discharges combination fulfilling all the existent constraints.

IV. Future Work

As future work we plan to develop an adequate evolutionary algorithm for the prioritization process and to evaluate its characteristic parameters. We will consider the use of swarm intelligence.

Moreover, we plan to incorporate this metaheuristic into the whole procedure of the Coordinating Agent and to incorporate it in the MAS. Finally, we foresee to evaluate the overall operation of the MAS.

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