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# Towards an Agent-Based design for the management of Urban Wastewater Systems

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**Abstract:** Urban Wastewater Systems (UWS) have an important role in nowadays growing and urbanized areas. The management of the water and wastewater cycle in these areas is complex since wastewater sources are both heterogeneous and rapidly changing. Moreover, it implies to deal with different spatial and temporal references and to adapt to the changing conditions that might appear in both natural and urban environments. New paradigms are required to be undertaken when designing and modelling this complex dynamic system, since the need to communicate the embedded elements is essential for an efficient and effective management and a better understanding of the UWS. Multi-Agent Systems (MAS) are systems composed of several *software agents* that collectively are capable of reaching goals that are difficult to achieve by individuals. The concept of MAS shapes an important step towards the possibility to design the system to reach decisions in a more collaboratively and integrated way. The paper proposes a primary but consistent design of UWS using an agent-oriented methodology (GAIA). The agents in the UWS are designed in terms of the roles they can perform, so the activities and protocols they act upon, which finally depict a detailed description of the relations in between them. A general hierarchy between the agents is also given (*e.g.* the acquaintance model). Therefore, the agent-oriented design enables to depict both micro and macro level design of the UWS management.

**Keywords:** Urban Wastewater System (UWS); Integrated Management; Multi-Agent Systems (MAS); Agent Design

## 1 INTRODUCTION

The efficient and effective management of water and wastewater resources is a complex task. In the Mediterranean Catalan region most of the urban catchments are designed as unitary systems that collect both domestic and industrial wastewaters, each one presenting different and variable flows and polluting loads. In this context, the industrial component in the Urban Wastewater System (UWS) is of special concern mainly for urban Wastewater Treatment Plant (WWTP) managers. One of the most important reasons is the variability on its composition, changing widely depending on the function and activity of the particular industry. Whereas they generate relatively constant flow rates during production, these flow rates change markedly during cleanup and shutdown. This implies that urban Wastewater Treatment Plants (WWTP) often have to assume flows and loads that are not always predictable: industrial wastewater discharges are difficult to forecast and they cause both, long-term (seasonal) and short-term (hourly, daily and weekly) variations. Consequently they may enter in conflict with the real possibilities of wastewater treatment plants' capacity to treat with a minimum quality before pouring to a receiving media (*e.g.* river).

The UWS have several features that make them difficult to represent and model: they evolve over time; they have a multi-spatial coverage (*e.g.* a discharge in the upper part of the river may affect lower parts of the river); they involve interactions between physical-chemical and biological processes; on top, many of the processes involved are stochastic [Poch *et al.*, 2004; Rizzoli *et al.*, 1997]. All of these features require a multi-disciplinary expertise as well as ideal tools to successfully cope with these characteristics. Until now there has been a long modelling tradition of sewers, treatment plants and receiving waters

describing performance in terms of individual needs and objectives and more recently integrating the different parts to allow the wastewater system to be considered as a single system [Fu *et al.*, 2008; Vanrolleghem *et al.*, 2005; Butler *et al.*, 2005; Pleau *et al.*, 2005 and Schütze *et al.*, 2004]. These elements have typically been built using deterministic descriptions of the fundamental mechanisms and processes (*e.g.* hydraulics in sewer systems, wastewater treatment and quality change modelling in rivers, etc.). But the complexity of environmental domains makes it difficult to wholly describe the system in terms of numerical models that have an important limitation in describing the interactions among the elements.

Some of the conceptual challenges that the present mathematical models can not tackle when performing an integrated urban wastewater management can be overcome using the *agent paradigm*. The need to cope with the dynamics and emergent situations (*e.g.* the incorporation of new industries to the system) requires application components to interact in more flexible ways. The characterization in terms of agents has proven to be a natural abstraction to many real world problems, having convinced researchers and developers in a wide variety of domains [Jennings *et al.*, 1998; Nwana, 1996; Athanasiadis, 2005] of the great potential of multi-agent solutions. The Multi-Agent System can be built describing numerous *agents* with a different degree of complexity, according the information and knowledge available. The complexity and degree of knowledge can be improved without the necessity to modify all the system as they are intended to be systems with high modularity and scalability [Luck *et al.*, 2005].

We consider UWS as a systematic process where effective decisions, policies and strategies are designed to lessen the impacts of humans and industrial activities on a river basin. All activities, including structural and non-structural measures to prevent (avoid) or to limit (mitigate) adverse effects are considered in this definition. As citizens, governments and industrialists seek for more integrated information systems the specification of UWS gets more complex. Among other: Accessibility to information, Interoperability and Coordination stand as issues to be solved.

In this paper we propose an agent-oriented approach to design the system whose final aims are 1) in normal conditions to make the UWS work to achieve the *best* possible quality of the river and to avoid leading the system to disturbed/emergency situations, 2) in emergency or disturbed conditions, get the minimum possible impact (stressing on disturbances of industrial activity in the system) and 3) to improve the context of decision-making process in the prevention of risks in a basin by focusing on the efficiency of information management and assessment services, thus improving the interoperability among the involved actors and their information systems. The agent-based model for the wastewater system is further described, making special emphasis on the description of 1) the roles and their instantiations for each agent type presented in section 3, 2) the obligations in terms of responsibilities, permissions and constraints of each role shown in section 4, and 3) the communication and interaction patterns among the agents (section 5). Hence, the results of applying agent-based oriented methodology for the design of a UWS are presented, highlighting the conceptual models obtained. In section 6 a summary of the main advantages offered by this new conceptualization as well as some of the most important future challenges are provided.

## 2 METHODOLOGY: AGENT-ORIENTED DESIGN

Agent-oriented approaches can improve the ability to model, design and build complex systems. The development of MAS requires at least three important features to be resolved [Zambonelli *et al.* 2003, Tran *et al.* 2007, Biswas 2008]: 1) the agent internal design, that is to identify the agent types and their roles; 2) the agent interaction design, that is to design the coherent blocks of activity in which agents will engage to realize their roles and their properties and the possible exchanged messages; and finally 3) the MAS organization model, describing the acquaintances and hierarchical organization structure, that is the communication pathways between the different agent types.

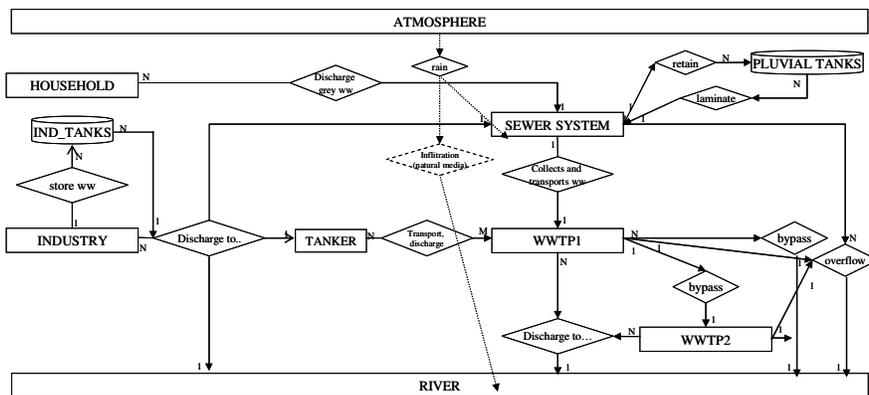
For the proposed agent-oriented approach the extended version of GAIA Methodology [Zambonelli et al., 2003] to model the agents is used. GAIA is a general methodology that supports both the micro-level (agent structure) and macro-level (agent society and organization structure) conceptualization for agent-based system development. According to this methodology (for a comparison with other existing AOSE methodologies see Tran et al. [2008] and Biswas [2008]), to solve a given problem requires designing a system as three components:

- *Environment*: involves analysing all the entities and resources that the agents in Multi-Agent Systems (MAS) can use when working for a common goal. Actions are performed by the agent on the environment, which in turn provides percepts to the agent [Russell and Norvig, 2003]. Consequently, for our application-specific purposes it will be very important to identify, model and shape the characteristics of the involved environment. However the environment is not always physical (including, among many other percepts, the chemical and physical measures of river quality); sometimes it will be virtual (e.g. legislative framework and rules).
- *Roles*: since agents interact in some organisational setting that influences the agent behaviour, roles define what an agent is expected to do in the organization itself and with respect to other agents; thus, the roles are the specific tasks that an agent has to accomplish in the context of the overall system.
- *Interactions*: define interdependencies among agents that are illustrated using protocols. The interaction model describes the characteristics and dynamics of each protocol (e.g. when, how and by whom a protocol has to be executed).

In the next section the agent-based model for the wastewater system is further described making special emphasis on the explanation of 1) the roles and their instantiations for each agent type, 2) the responsibilities, permissions and constraints of each role, and 3) the communication and interaction patterns between the agents.

### 3 THE AGENT MODEL FOR THE WASTEWATER SCENARIO

In this section the results of the analysis process that enable to identify the agent types, the roles of the system and the assignment of these roles to the agents are shown. We propose the modelling of a simplified UWS, whose main elements and processes are depicted in Figure 1. Accordingly, the understanding of the proposed MAS is an organization of entities (squares in Figure 1), represented as agents interacting



**Figure 1.** Urban Wastewater System: wastewater flow diagram with components and processes included in the study; each of the squares represents an agent and each of the rhombuses specific actions and/or processes occurring in the system.

A partial Agent Model is shown in Figure 2, where roles have been assigned to the agent types. In Table 1 and 2 the WasteWaterProducer (WWP), WasteWaterTreatment (WWT)

and RiverProtection (RP) roles are, respectively, fully described, in order to show the detailed design (note that *activities* are tasks an agent performs without interacting with other agents, thus it will be not necessary to describe a protocol for them).

From the list of protocols, activities, responsibilities and liveness properties of roles described in Table 1 and 2, it is possible to more easily describe the functions of the agents. In the following section a description of those services introduced in the previous tables is given.

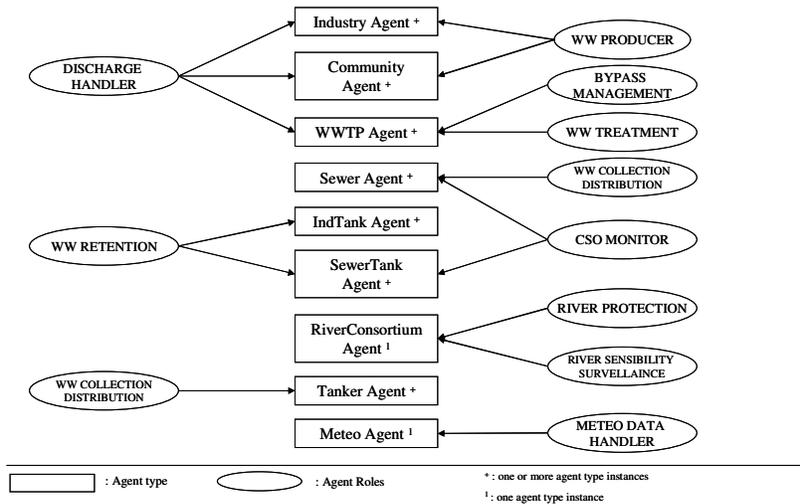


Figure 2. Agent Model for the wastewater management scenario

Table 1. Schema for the WasteWaterProducer and WasteWaterTreatment role

Role:	WasteWaterProducer (WWP)	WasteWaterTreatment (WWT)
<b>Description:</b>	Keeps track of individuals - industries, communities - quantity and quality of wastewater produced as consequence of their activity. Informs the receiver of the discharge about it. Calculate the cost of discharge.	Keeps track of wastewater flow that arrives at WWTP (according to treatment capacity – design parameters and yields – and hydraulic capacity) and controls the influent; supervise and control the treatment process, informing about the WWTP state if asked and giving alarms when a problem occurs; manages WWTP control set points.
<b>Protocols &amp; Activities:</b>	<u>CheckFlow</u> , <u>CheckPollutants</u> (BOD, COD, TSS, nutrients -N and P -), <u>CheckToxicity</u> (heavy metals and other inhibitory substances), <u>UpdateDB</u> , <u>InformDischargeCharacteristics</u> , <u>CalculateDischargeCost</u>	<u>CheckInfluent</u> (flow, pollution, toxicity), <u>SuperviseControl</u> (ATL <sup>1</sup> ), <u>InformState</u> , <u>GiveAlarms</u> , <u>OperateSetPoints</u>
<b>Permissions:</b>	Reads: chemical sensors, flow meters, toxicity indicators, tests Updates: DataBases (IndDB, ComDB, wwtpEffDB)	Reads: entrance sensors, on-line and off-line data, Writes: WWTP state, alarms Executes: control commands
<b>Responsibilities</b>	<b>Liveness:</b> WWP=( <u>CheckFlow</u> . <u>CheckPollutants</u> . <u>CheckToxicity</u> ) <sup>∞</sup>    <u>CalculateDischargeCosts</u> <sup>∞</sup> . <u>UpdateDB</u> <sup>∞</sup> . <u>InformDischargeCharacteristics</u> <b>Safety:</b> True	<b>Liveness:</b> WWT=( <u>CheckInfluent</u> . <u>SuperviseControl</u> ) <sup>∞</sup> . <u>InformState</u> <sup>*</sup> . <u>GiveAlarm</u> <sup>*</sup> . <u>OperateSetPoints</u> <sup>*</sup> <b>Safety:</b> True

<sup>1</sup> ATL makes reference to the supervisory system to support WWTP operation. For more information see Rodriguez-Roda et al. [2002], Comas et al. [2003] and Poch et al. [2004].

**Table 2.** Schema for the RiverProtection role

<b>Role:</b>	RiverProtection (RP)
<b>Description:</b>	Updates the ecological status of the river and its dilution capacity (flow, stational variations, maintenance flow...) and informs about it. Collects toxicity opinions and studies from different sources about the possible different source and type of pollution that might arrive to the river. Updates the database available about the different causes-effects of toxicity into rivers.
<b>Protocols &amp; Activities:</b>	CheckRiverQuality, CheckDilutionCapacity, UpdateInfoDB, InformRiverState
<b>Permissions:</b>	Reads: sensors from automatic stations, river quality model, maintenance flows Writes: state of river
<b>Responsibilities</b>	<p><b>Liveness:</b> <math>RP = \text{CheckRiverQuality}^\circ \cdot \text{CheckDilutionCapacity}^\circ \cdot \text{UpdateInfoDB}^*</math> . InformRiverState</p> <p><b>Safety:</b> RiverQuality <math>\in</math> quality goals: very good, good or moderate categories DilutionCapacity = Discharged Flow (annual average) / RM Flow (maintenance flow) &lt; 50 %</p>

**4 THE SERVICES MODEL FOR THE WASTEWATER SCENARIO**

Table 3 describes the service model. Take notice that for each service there is a protocol described in terms of a role(s) responsible for starting the interaction (*initiator*), a responder role(s) with which the initiator interacts (*partner*), the information used by the initiator role while enacting the protocol (*inputs*) and the information supplied by the protocol responder during interaction (*outputs*).

**Taulla 3.** Service model for the wastewater management scenario

SERVICE	INITIATOR	PARTNER	INPUT	OUTPUT
InformDischarge Characteristics	WWP	WWCD WWT	Results of CheckFlow, CheckPollutants and CheckToxicity activities	Values for (Flow, Pollutants, Toxicity) characteristics
InformState	WWT	RP	ATL data acquisition and knowledge management modules	State of the plant
GiveAlarms	WWT	RP, WWP WWCD	ATL simulation module	Alert if a problem occurs into to the plant
InformRiverState	RP	WWT	River Quality data acquisition	Value for ecological status Value for dilution capacity effect

Notice that, in Table 3, some of the services' inputs are indeed the results of some activities performed by a specific role. Although activities do not require a protocol (there is not an initiator – partner tuple), it might be interesting to describe them in order to give fully comprehension to the services model. Thus, the activities on Table 4 are those of the WWP, WWT and RP roles. For example, the results of the activities *CheckFlow*, *CheckPollutants* and *CheckToxicity* performed by the WasteWaterProducer are the inputs for the protocol *InformDischargeCharacteristics*, since the initiator role will transfer them to the partner. So, in this case, there is a separation in between the fact of checking and acquiring on-line and of-line data from the fact to pass and give this information.

**Table 4.** Activities performed by the WWP, WWTP and RP roles

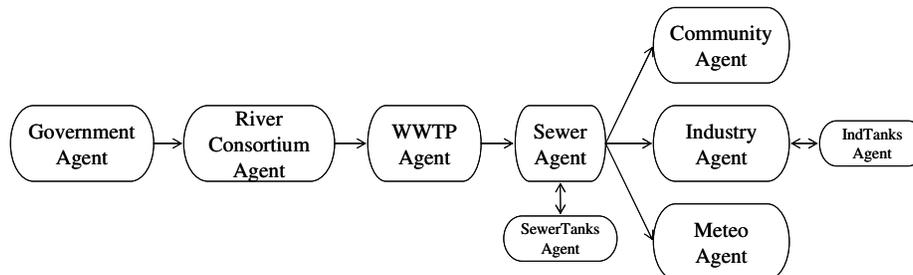
Activity (role)	INPUT	OUTPUT
CheckFlow (WWP)	On-line flow sensors, flow databases (flow records) from Industry, Community, WWTP and Tanker Agents. Tanker capacity.	Wastewater flow rates (m <sup>3</sup> /hour, m <sup>3</sup> /day, m <sup>3</sup> /year). Volume in the tank.
CheckPollutants (WWP)	On-line data, off-line data (from tests)	Values for the next parameters: BOD, COD, TSS, TN, TP, KjN, N-NH <sub>4</sub> <sup>+</sup> , Temperature, pH
CheckToxicity (WWP)	Toxic tests	Values for equitox and/or specific pollutants

Activity (role)	INPUT	OUTPUT
CalculateDischargeCosts (WWP)	The price is a function of the quantity and quality wastewater parameters	Price (€/m <sup>3</sup> or total €)
CheckInfluent (WWT)	On-line flow sensors	Characteristics of influent water at wwtp (flow, pollution, toxicity)
OperateSetPoints (WWT)	ATL <sup>1</sup> control module	Change setpoint (DO, bypass, Qrec, Q <sub>WAS_primary</sub> , Q <sub>WAS_secondary</sub> )
CheckRiverQuality (RP)	Model for the river	Value for the ecological status of the river
CheckDilutionCapacity (RP)	Discharged flow and maintenance flow	Value for dilution capacity effect (annual average of discharged flow/maintenance flow of receiving media)

Note: BOD: Biological Oxygen Demand, COD: Chemical Oxygen Demand, TSS: Total Suspended Solids, TN: Total Nitrogen, TP: Total Phosphorous, KjN: Kjehdal Nitrogen, N<sub>NH<sub>4</sub><sup>+</sup></sub>: ammonia nitrogen, Temp: temperature, DO: Dissolved Oxygen, Qrec: Recirculated Flow, Q<sub>WAS\_primary</sub>: waste activated sludge from the primary clarifiers, Q<sub>WAS\_secondary</sub>: waste activated sludge from the secondary clarifiers.

### 5 THE ACQUAINTANCE MODEL FOR THE WASTEWATER SCENARIO

In the previous section the type of information and the result of the communication protocols was described, whereas inhere the focus is on the flow of information, that is who can communicate with whom. Notice that the information provided in this section is consistent with the protocols described previously (in the sense that the interchanged information between roles when performing the communication protocols is coherent with the communication that can be established in between the specific agents that play such roles). To describe the interrelationships between the agents a parallelism with the real water flux is helpful. So in this case, we infer that the agents representing the origin of wastewater (*i.e.* industries, communities) communicate with the possible agents representing the reception of this wastewater (*i.e.* sewer, tanker or WWTP); the same way, this second level of agents is controlled by an upper level who can observe all the levels above them (*i.e.* the River Consortium, an entity in charge of sanitation infrastructures of a particular catchment and representing the interests of the river provided by other interested stakeholders such as ecologists or other environmental entities) (see Figure 3).



**Figure 3.** The acquaintance model for the wastewater system. Arrows show the possible relationships between agents; their direction indicates that agents can receive information – maintain communication – with agents in the above levels.

At catchment scale, the agents’ metaphor works and it is clear that it helps to depict all the relevant elements of this scenario. This is a challenging, that of combined multirisk planning, entails a demand for high level of collaboration and inter-operation among the involved actors and information entities. In this sense we are in line with some EU-funded efforts, like ORCHESTRA [Denzer *et al.*, 2005], that are open architectures to support interoperability in environmental risk management.

## 6 CONCLUSIONS AND CHALLENGES

UWS activities involve multiple organizations at various administrative levels, each one having their own systems, services and interests. In many cases, the capacity (and will) to share relevant information between organizations is limited. In the best of the cases is forced by law. This limits the chances of preventing the impact of human activities in the river. The use of Agents is meant to challenge the problems related with information sharing and to improve the interoperability among actors in order to support better coordination and more informed decision-making.

The results of applying the agent-oriented design for the UWS are three different but interrelated models: the agent model, the service model and the acquaintance model for the wastewater scenario. Such design, in terms of agents, adds several useful aspects to the modelling tasks *w.r.t.* having simply objects or elements. Some of the advantages encountered while conceptualizing the urban wastewater system using an agent-based oriented design are the following:

1. It provides a way to better integrate data and information from heterogeneous sources and to better distribute the data.
2. It provides the possibility to establish a more direct and natural communication and coordination between the elements and the possibility to keep the history of the course of the interaction between them. However, although communication between the agents can multiply their effectiveness [Wooldridge 2001; Müller 1996], for each specific implementation it should be evaluated to what extent and for what tasks inter-agent communication significantly improve the desirable performance in comparison with other local methods for conflict resolution.
3. It provides a major abstraction and consequently a higher adaptability to the environment and to changing conditions, thanks to the capacity of multi-agent systems to accept new elements (*i.e.* new industries entering the system could be easily modelled according the abstractions provided here for industry agent and roles).
4. Moreover, the possibility to coordinate their actions by working in a cooperative fashion adds a greater value than the one that can be obtained from any individual or even integrated mechanistic model. For instance, in the urban wastewater domain, some activities need to be coordinated because of shared resources (*i.e.* the WWTP), or because some activities depends upon others activities (*i.e.* industrial discharges require a permission from water authorities) or just because, intuitively, working proactively agent's self-utility increase.

We have shown that agent-methodologies are a useful tool to analyse the system and better explain *how* it should work. Also, are important to raise awareness of the advantages and problems of open systems. The development of agents, independently of their complexity, help to more accurately describe the activities and processes occurring into the system. In special, those related with: Accessibility to information, Interoperability and Coordination. However, work still need to be done in order to fully implement the system in the urban wastewater management scenario.

Evaluation phase will be based on the execution of existing and well-documented cases of discharges that will be used as gold standards. In the long run the evaluation will be performed on a real basin.

Apart from using the models depicted in this paper to evaluate, through agent-based simulation, some (behavioural) aspects of the UWS agents, some of the future challenges of this research include the construction of agent reasoning patterns in order to introduce argumentation over a proposed action among the involved agents.

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