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Improving waste water treatment quality through an auction-based management of discharges

Javier Murillo[a], Dídac Busquets[a], Jordi Dalmau[b], Beatriz López[a] and Víctor Muñoz[a]

[a] *Institut d'Informàtica i Aplicacions,Universitat de Girona, Campus Montilivi, 17071 Girona, Spain, {jmurillo, busquets, blopez, vmunozs}@eia.udg.edu*

[b] *Laboratory of Chemical and Environmental Engineering, Universitat de Girona, Campus Montilivi, 17071 Girona,Spain, jordi@lequia.udg.edu*

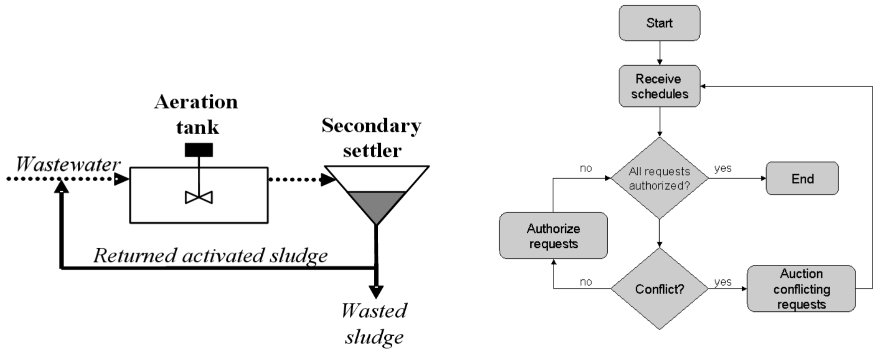
Abstract: This paper proposes the use of an auction process in which the capacity of a Waste Water Treatment Plant (WWTP) is sold to coordinate the industrial discharges. The main goal of coordination is to manage the wastewater inflow rate and pollutants to improve the WWTP operation. The system is modeled as a multi-agent system where each industry is represented by an agent, another agent represents the influent coming from the domestic use and one more agent represents the WWTP. When the maximum level of the flow or the maximum concentrations of some components exceed the plant's capacity, an auction starts. In the auction, the WWTP agent is the auctioneer that sells its capacity (resources) and the industry agents are the bidders that want to buy the resources. In the auction process the bidders send their bids to the auctioneer and the auctioneer decides which are the winners. The winners will discharge to the sewage system and the losers will have to wait for the next opportunity. After the coordination process, the resulting wastewater discharge schedules of the industries have been analyzed using the IWA/COST simulation benchmark as a case study. The results obtained through this simulation protocol show that the auction-based coordination mechanism using both pollution and hydraulic capacity constraints accomplishes the goal of improving the effluent quality, achieving a reduction in the impact of industrial discharges up to 20,99%.

Keywords: Discharge coordination; Integrated management; Water quality; Auction mechanisms; Benchmark; BSM.

1. INTRODUCTION

A Waste Water Treatment Plant (WWTP) receives the polluted wastewater discharges coming from different industries. Nowadays the most common wastewater treatment is the activated sludge process. The system consists in an aeration tank in which the microorganisms responsible for treatment (i.e. removal of carbon, nitrogen and phosphorous) are kept in suspension and aerated followed by a liquid-solids separation, usually called secondary settler. Finally a recycle system for returning a fraction of solids removed from the liquid-solids separation unit back to the reactor, whereas the other fraction is wasted from the system (Metcalf and Eddy [2003]; Figure 1(a)).

The treatment capacity of the plant is limited, therefore all pollutants arriving at the WWTP should be under certain limits; otherwise, the wastewater could not be fully treated and the river would be polluted. Currently, there exist regulations intended to achieve this goal by assigning a fixed amount of authorized discharges to each industry. However, they are not sufficient to guarantee the proper treatment of the wastewater. The problem is that, although these regulations enforce industries to respect the WWTP capacity thresholds, they do not take into account that simultaneous discharges by different industries may exceed the WWTP's thresholds. In such a case, no industry would be breaking the rules, but the effect would be to exceed the WWTP capacity. Besides, industry discharges add complexity to the waste water treatment system, given that the high variability in influent pollutants composition hampers the WWTP operation because they must discharge under certain limits.



(a) (b)

Figure 1. Activated sludge process (a). Coordination system (b).

As an alternative and more flexible regulation mechanism, we propose the use of an auction process in which the capacity of the WWTP is sold. Auctions are a popular mechanism in economy, usually used to distribute shared resources among different agents (Chevaleyre et al. [2006]). Auctions are currently being used in several industrial scenarios (Bichler et al. [2006]), as the electricity market in which different kinds of energies are auctioned in order to favour the use of non pollutant sources of energy. Recently, auctions have been also considered to deal with natural resources, as CO_2 emissions. In these models, each industry bids for CO_2 emission credits, in such a way that high pollutant industries pay for a lot of emission credits (unless they install some kind of filters in their factories), while industries with non pollutant processes do not need any emission credit, keeping their manufacturing process at a lower cost. Moreover, this approach is in line with a more integrated management of the river basin (Butler and Schütze [2005]) taking into account not only the plant, but also the rest of the components of the treatment system, such as the industries and their discharges. In this context, it seems suitable to raise the possibility of using auctions to deal with wastewater resources, as in a WWTP. This paper presents a first approach to this possibility.

The paper is organized as follows. In Section 2 we present the coordination system, describing in detail each of the involved steps. The implementation of a first prototype is described in Section 3. In Section 4 we discuss the experimental results obtained through simulation and Section 5 derives some conclusions.

2. AUCTION-BASED MANAGEMENT

The wastewater treatment problem could be solved using a centralized approach, where given all the planned discharges from the industries, a new schedule for each of them would be generated, in a way that the capacities of the plant are not exceeded at any time. Centralized approaches imply that a central scheduler would make all the decisions. However, such decisions should be made by each of the industries, since they may not be willing to disclose private information related with the production process upon which their decisions are based. Thus, in order to preserve privacy, other coordination mechanisms should be considered.

In the waste water treatment scenario there is one central element, the treatment plant, who assumes the role of coordinating the discharges of the industries. Then, the plant's capacities are modeled as individual resources, shared by all the industries. Each time a conflict in a resource occurs (i.e. the capacity is violated) an auction is started in order to determine which of the conflicting discharges will be authorized to discharge and which will have to be delayed. We have chosen auctions as they are a well-known mechanism to distribute shared resources among competing agents when information privacy is a concern.

We assume that each industry has a retention tank of a given capacity, where it can store a discharge whenever it is not authorized, and empty it later on. We also assume that each industry can estimate in advance the discharges that it will generate according to the production process. Although this estimation may differ from the real discharges, they help in the process of coordinating all the discharges and so, adjust properly the WWTP.

In the next two sections we explain in more detail how we have modeled the WWTP scenario as a multi-agent system, as well as the coordination process based on auction mechanisms.

2.1 Multi-agent modeling

Our system, modeled as a multi-agent system, reflects the physical separation between the participants (the plant and the different industries) and also supports privacy in the decision making process of each of the involved agents. Multi-agent systems allow the implementation of complex interactions among the different agents through an appropriate coordination mechanism. In our WWTP scenario, the WWTP agent is the agent who owns the resources (hydraulic and pollution capacities) and the industry agents want to use them.

The process for coordinating the different discharges coming from the industries is depicted in Figure 1(b). Firstly, the industries inform the treatment plant about their scheduled discharges. These schedules contain the set of discharges that they plan to perform in a given period of time, and for each discharge the information about its starting time, duration, flow and contaminant levels is also included. Hence, a schedule from an industry k is described as $S_k=\{d_1,\ldots,d_n\}$ where n is the number of discharges contained in the schedule and each discharge d_i is defined as $d_i = \{s_i, t_i, \bar{q_i}\}$, where s_i stands for the start time, t_i is the duration and $\bar{q_i}$ is a vector containing the flow and contaminant levels of the discharge. The start time of discharges can be modified depending on the industries location: when a difference between the discharge time and the discharge arrival to the WWTP exists this delay should be added to s_i.

The WWTP agent, upon reception of all the industries' discharge schedules for a given day (or any different predefined period of time), starts checking for conflicts. A conflict arises when the discharges planned to be performed at a given time violate any constraints (see Section 3.2 for their definition). Whenever a conflict is detected, the involved industries (the industries whose discharges are scheduled at the time of the conflict) are informed about it, and an auction is started to solve it, forcing industries to modify their schedules. The resolution is done in a sequential way, treating one conflict at a time in chronological order. This process is repeated until all the discharges have been authorized, and the result is that each industry has a new schedule, and these resulting schedules do not produce any conflict.

The unauthorized discharges should not cause problems in the production processes of the industries. In case an industry agent has to reschedule its discharges, its behavior is the following: it first tries to store the rejected discharge into the tank; the discharge of the tank is then scheduled as the first activity of the agent once the current conflict has finished. Conversely, if the industry has its tank already full, the discharge will be performed anyway[1]. However, the influent coming from the domestic use does not have any retention tank and, consequently, its discharges cannot be modified.

Note that it is not necessary to know in real-time the industrial discharges, since the coordination process is done offline, for example one day before.

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[1] It is possible to minimize these situations in the auction mechanism, following for example Muñoz et al. [2007]

2.2 Auction mechanism

Once the involved discharges in a conflict have been detected, their corresponding agents (industries) are informed about the conflict and the auction process begins. The WWTP agent assumes the *auctioneer* role who is in charge of selling its flow and pollution capacities resources and the industry agents assume the *bidders* role. The goal of the auction is to select a subset of industries, which will be authorized to perform their discharges, while the remaining should have to be delayed (stored in the tank). The selection criterion is based on the bids submitted by the agents. These bids represent the urgency that each of them has to perform the discharge. A high bid indicates that the agent really needs (or wants) to perform the discharge, while a low bid indicates that the agent could delay the discharge and therefore it can miss the opportunity to perform it at the auctioned time. For example the bid value v_i of the industry agent *i* could be calculated dividing tank occupation of industry by the total tank capacity of industry.

Note that the auction process allows industries to express their interest of discharging at a given time through the bidding policy, conversely to other centralized approaches that forces industries to discharge at a given time. Even that we have used the tank capacity for bidding generation, other policies can be implemented according to the industries strategies (prices, etc.). Then, the auctioneer clears the auction (i.e. determines which discharges to authorize) by solving the Winner Determination Problem (WDP) (Kalagnaman and Parkes [2005]). Particularly, since the auctioneer offers multiple (but limited) units of different items, and bidders submit bids for a certain number of units of each item, we are dealing with a multi-unit combinatorial auction whose WDP is modeled according to the Equation 1.

$$\begin{aligned} &\max \sum_{i=1}^{NC} x_i \cdot v_i \\ &s.t. \sum_{i=1}^{NC} x_i \cdot q_{i,j} \leq Q_j \qquad \forall_j \in C \end{aligned} \tag{1}$$

where *NC* is the number of conflicting discharges, $x_i \in \{0,1\}$ represents whether discharge *i* is denied or authorized, $v_i \in \Re^+$ is the bid value for discharge *i*, $q_{i,j}$ is the capacity requirement of the resource *j* for the discharge *i*, Q_j is the resource *j* capacity and *C* is the set of resources. In our case, the items represent the flow and the contamination levels whose available units are determined by the capacities of the plant. This problem is similar to the multi-dimensional Knapsack problem (Kelly [2005]).

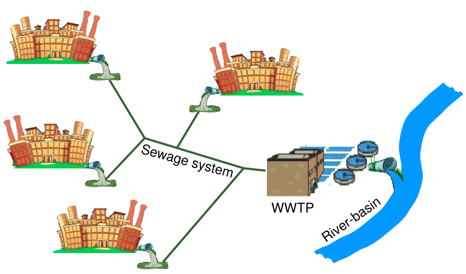

Figure 2. Case study.

3. CASE STUDY

Our case study is a typical wastewater treatment system with 4 industries (depicted in Figure 2). The industries discharge their wastewater to the sewage system, which directs it to the WWTP. The plant, once the wastewater has been treated, puts it back to the river. The first industry is pharmaceutical, which is increasing its discharge flow during the week and does not discharge during the weekend. The second one is a slaughterhouse that discharges a constant flow, except at the end of the day when it increases. The third one is a paper industry that discharges a constant flow during the seven days of the week. The fourth one is a textile industry, whose discharges flow oscillates during the day. Industries discharges are added to the effluent of the city which is fixed and cannot be coordinated. Altogether represent the WWTP influent. Thus, the output of the auction system is a set of coordinated discharges that is entered as input for the WWTP.

3.1 IWA/COST Simulation Benchmark

As a model for the WWTP, the IWA/COST Simulation Benchmark has been used. This simulation protocol has resulted in more than 100 publications worldwide (Jeppsson et al. [2006]) and provides several tools such as control evaluation, prediction, estimation of biomass activities and effluent quality parameters. The Benchmark Simulation Model N1 (BSM1) layout contains the Activated Sludge Model N1, ASM1 (Henze et al. [1987]) for two anoxic and three aerobic tank reactors, followed by the Takács ten-layer model for the secondary settler (Takács et al. [1991]). Model influent files include 14-days weather disturbances (i.e., dry, rain and storm weather) with 15-minutes sampling. In our case the dry BSM1 influent has been selected and modified with a set of real data provided by the Laboratory of Chemical and Environmental Engineering (LEQUIA) to represent industries discharges. Among the outputs the model provides the Effluent Quality Index (EQI) and the Influent Quality Index (IQI), both are a weighted calculation of the amount of pollutants (i.e. carbon and nitrogen in different forms) present in both the influent and the effluent of the model. They are used for the plant performance evaluation based on the total kilograms of pollutants present in the effluent and the influent (Copp [2002]). We have essentially considered the EQI and IQI values for the evaluation of the auction system. Likewise, the outcome of the benchmark permits us to observe the effects of the coordination mechanism on the quality of the treated wastewater.

3.2 Constraints

In order to coordinate the industrial discharges and improve the effluent quality, the following constraints have been defined:

- **Hydraulic capacity constraint**. This constraint ensures that the total flow arriving to the WWTP (from the influent and industrial discharges) does not exceed a certain threshold at any time. This threshold is called the Maximum Flow (MF).

  $$\forall t \in [0,T] : \sum_{i=0}^{N} flow_{i,t} \le MF \tag{2}$$

  where T is the final time of the simulation, N is the set of industries (including the influent) and $flow_{i,t}$ is the flow discharged by industry (or influent) i at time t.

- **Pollution constraints**. These constraints ensure that the concentrations of certain components arriving to the WWTP do not exceed their respective thresholds at any time. There are 4 constraints, for the following components: COD (Chemical Oxygen Demand), BOD (Biological Oxygen Demand), TKN (Total Kjeldhal Nitrogen) and TSS (Total Suspended Solids). Each constraint is defined as follows:

  $$\forall t \in [0,T] : \forall c \in C : \frac{\sum_{i=0}^{N} conc_{i,c,t} \cdot flow_{i,t}}{\sum_{i=0}^{N} flow_{i,t}} \le MC_c \tag{3}$$

  where C is the set of components (COD, BOD, TKN and TSS) and $conc_{i,c,t}$ is the concentration of component c produced by the industry i or influent at time t. MC_c is the maximum concentration threshold for component c.

4. EXPERIMENTAL SETUP

To test the coordination mechanism we have implemented a prototype of the system, using Repast[2], a free open source software framework for creating agent based simulations using Java language. The simulation reproduces the process and the communication between the plant and the industries performing discharges. We have created one agent to represent the plant and another for each of the industries. The free linear programming kit GLPK[3] has been used to solve the winner determination problem related to each auction.

In order to compare the results obtained with and without auction-based management, three different scenarios have been defined.

- The first scenario considers the influent (dry) without industrial discharges. This scenario shows the wastewater IQI and EQI when simulating with only domestic wastewater (i.e. BSM1 default influent file).
- The second scenario adds to the influent the industrial discharges, without using the auction-based management mechanism. This scenario is useful to calculate the impact of industrial discharges in the WWTP effluent. None of the discharges violate current legislation but there is a deterioration of water quality (increase of IQI and therefore EQI) due to industrial discharges. We have measured such deterioration.
- The third scenario is the same as the second one but using the auction-based management mechanism. This scenario is useful to determine the benefits of the proposed system in terms of EQI.

5. AUCTION-BASED MANAGEMENT MECHANISM PERFORMANCE

The experimental results have been obtained with the simulation protocol BSM1 in the three different scenarios previously described. In order to evaluate the system the effluent quality has been considered.

<table>
<tr><th colspan="2"></th><th>IQI $\left(\frac{Kg.poll \cdot unit}{day}\right)$</th><th>EQI $\left(\frac{Kg.poll \cdot unit}{day}\right)$</th><th>Increment $\left(\frac{Kg.poll \cdot unit}{day}\right)$</th><th>Reduction</th><th>Constraints</th></tr>
<tr><td colspan="2">Influent (scenario 1)</td><td>42042,81
(20195,42)</td><td>7556,54
(2219,93)</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td rowspan="7">Influent and industries</td><td>w/o auction based mng. (scenario 2)</td><td>59092,21
(20080,39)</td><td>9127,37
(2303,71)</td><td>1570,83</td><td>-</td><td>-</td></tr>
<tr><td rowspan="6">With auction based mng. (scenario 3)</td><td>59163,90
(16527,12)</td><td>8958,64
(1935,64)</td><td>1402,11</td><td>10,74%</td><td>R1</td></tr>
<tr><td>59139,67
(16225,36)</td><td>8901,23
(1931,82)</td><td>1344,70</td><td>14,40%</td><td>R2</td></tr>
<tr><td>59157,73
(15854,09)</td><td>8900,13
(2073,70)</td><td>1343,60</td><td>14,47%</td><td>R3</td></tr>
<tr><td>59126,16
(16086,98)</td><td>8886,15
(1906,97)</td><td>1329,61</td><td>15,36%</td><td>R4</td></tr>
<tr><td>59158,62
(18489,36)</td><td>9043,95
(2162,55)</td><td>1487,42</td><td>5,31%</td><td>R5</td></tr>
<tr><td>59132,39
(13378,48)</td><td>8797,63
(1729,65)</td><td>1241,10</td><td>20,99%</td><td>R6</td></tr>
</table>

Table 1. Results obtained with the benchmark BSM1 in different scenarios.

Table 1 shows the results obtained with the different simulations. The first column is the Influent Quality Index (*IQI*) measured with BSM1, integrating the last seven days of

[2] REPAST Agent Simulation Toolkit, http://repast.sourceforge.net
[3] GLPK Gnu Linear Programming Kit, http://www.gnu.org/software/glpk

weather simulation (Copp [2002]) with the standard deviation in brackets. The second column corresponds to the EQI measured by the benchmark with the standard deviation too. The third column (*Increment*) represents the difference in the *EQI* value between the first and the other scenarios; this value represents the impact of the industrial discharges in the wastewater. The fourth column shows the reduction in percentage on the value *Increment* when using the coordination mechanism. Finally, the fifth column (*Constraints*) indicates the set of constraints thresholds used for the coordination.

Six different constraints have been considered. *R1* is related to the maximum flow (MF), setting it to 25000 m^3/day; *R2* sets the Maximum TSS to 275 mg/l; *R3* dictates a Maximum TKN of 55 mg/l; *R4* states BOD = 234 mg/l; *R5* states Maximum COD = 575 mg/l and finally *R6* contains these constraints: Maximum flow = 32500 m^3/day, Maximum TSS = 275 mg/l, Maximum TKN = 50 mg/l, Maximum BOD = 260 mg/l and Maximum COD = 100 mg/l (Copp [2002]).

The results show that the value of *EQI* obtained in the first scenario is 7556,54 Kg poll·unit/day. When the industrial discharges are added to the influent in scenario 2 the value of *EQI* becomes 9127,37 Kg poll·unit/day, therefore the industries are causing an increase of 1570,83 Kg poll·unit/day. The other data of the table corresponds to the executions of the benchmark in the third scenario with coordinated data and using different sets of constraints, showing that when the auction-based management mechanism is used the *EQI* is reduced and consequently, the impact of industrial discharges (*Increment*) is smaller. In the best case (set of constraints *R6*) the impact is reduced up to 20,99%. According to *t-test*, the values of the mean and standard deviation of *EQI* in the second scenario and the best *EQI* obtained in the third scenario (set of constraints *R6*) are statistically extremely significant.

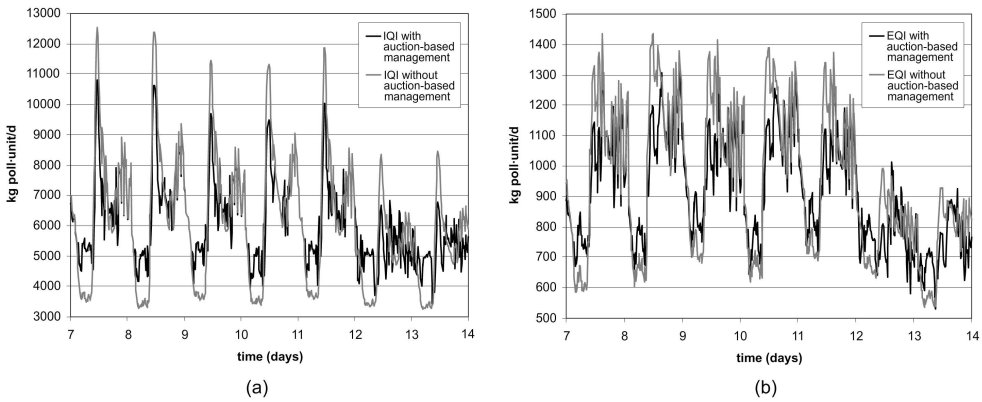

Figure 3. IQI during the 7 days (a), EQI during the 7 days (b).

Figure 3 (a) shows the values of *IQI* during the seven days with and without auction-based management. This picture shows that the auction-based management has lowered the upper values and raised the lower values. The steadiness in the *IQI* profile is important as it improves wastewater treatment by reducing the variability of the influent composition. This circumstance allows the WWTP to process more efficiently the pollutants and consequently achieve better results regarding *EQI*. Figure 3 (b) shows the comparison between the *EQI* values during the seven days with and without auction-based mechanism. Analogously to the Influent Quality Index (*IQI*), the values have also been homogenized.

6. CONCLUSIONS

In this work, the use of an auction-based management mechanism has been proposed in order to coordinate the industrial discharges. In this auction the WWTP assumes the role of the auctioneer that is selling its capacity as a resource, and the industries assume the role of bidders that want to buy the WWTP capacity. The auction determines which industries are going to be allowed to discharge to the sewage system and which are not. This process is repeated each times the hydraulic capacity constraint or the pollution constraints would be violated by the discharges in a given time (if they were not coordinated). The results obtained with the IWA/COST simulation shows that the auction-based management mechanism using pollution and hydraulic capacity constraint reduces the impact of industrial discharges up to 20,99%. This fact has been possible due to the IQI variability reduction, since it has made the WWTP able to process the pollutants more efficiently. Although the simulations do not completely match the treatment system in reality, it is a good starting point for showing to the public authorities and to the industries that the auction-based management approach could help improving both the WWTP operation and the water quality.

ACKNOWLEDGEMENTS

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