Coordinating Agents' Schedules through Auction Mechanisms

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Abstract. When selfish industries are competing for limited shared resources, they need to coordinate their activities to handle possible conflicting situations. Coordination can be performed at execution time or at planning and scheduling time. In this work we have focused on the latter case, coordinating agents' schedules, which in turn can be further divided depending on whether the goal is to coordinate existing schedules or to create new schedules for each of the agents. Since our agents have their individual schedules, we are faced with the problem of coordinating schedules that have already been generated. To address this task, we propose to use an auction mechanism to mediate between the agents. We also introduce a priority mechanism to add fairness to the coordination process. We have applied the proposed coordination mechanism to a water treatment system scenario, where different industries need to discharge their waste. We have simulated the behavior of the system, and the results show that using our coordination mechanism the plant can successfully treat most of the discharges.

1 Introduction

Multi-agent resource allocation [1] is the field concerning the distribution of resources amongst several agents. This field has several applications, such as supply chain management, production lines, e-commerce, etc. In such systems, each component is represented by an agent that has its own reasoning methods and strategies to achieve its goals with the use of shared limited resources. Regardless of these goals being common to all agents or not, some kind of coordination among them is needed so that the different actions taken do not end up in a conflicting situation in the use of the resources. In fact, coordination is a very important issue in multi-agent systems, since it directly affects the overall system performance.

The effectiveness of coordination relies on each agent complying with the rules of such mechanism. However, there are domains were agents are not obliged to participate in the coordination mechanism, and even if they do, they can decide whether or not to obey the outcome of this coordination. In such cases, the coordination mechanism should incentivize agents to participate in it. In the problem of combining existing schedules, one way of achieving this is by guaranteeing the agents that their original schedules are modified the least possible. We have focused our work on this latter issue.

The application domain we work with is the *waste water treatment system*, in which industrial discharges should be coordinated so that all of them can be fully treated by the plant. Obviously, this coordination should not cause problems in the production processes of the industries, since this could have dangerous effects (drastic changes may cause production delays, missed delivery commitments, etc).

The rest of the paper is organized as follows. We first describe in more detail the water treatment system. The coordination mechanism we propose is then presented. The experimental results are described next. Finally, some related work is discussed before concluding the paper.

2 Waste Water Treatment Systems

A typical water treatment system works as follows: the waste discharges from the industries are directed to the WWTP through the sewage system; these discharges are then treated in the plant, and the cleaned water is put into the river [2]. In order to ensure a proper treatment, two conditions must be met:

- Keep the *incoming water flow* below the WWTP hydraulic (i.e. absorbing) capacity ; otherwise, the overflowed water goes to the river without receiving any treatment.
- Keep the *contamination level* of the incoming water (defined by a set of quality variables: oxygen demand, nitrogen level...) below the WWTP treatment capacity. If the level of any of these variables is above the WWTP capacity, the water cannot be fully treated, increasing the contamination of the river.

Regulations regarding waste discharges already define the maximum amount of waste and the contamination level allowed to the industries. However, these are not sufficient to ensure the two conditions mentioned above. The problem is that regulations do not take into account that the WWTP thresholds can be exceeded when several industries discharge simultaneously. In such cases, none of the industries would be acting against the law, but the effect could cause overflow or overcontamination of the water arriving at the plant. Thus, it is easy to see that some coordination is needed in order to distribute the discharges so that they do not expose the plant to any dangerous situation. This coordination would improve the health of the river bank and its environment, and is directed towards a more integrated management of the river-basin. Being aware of this problem, the Laboratory of Chemical and Environmental Engineering of our university presented us the challenge of developing a mechanism to deal with these issues.

3 Coordinating Schedules

The treatment system scenario presented above poses a scheduling problem where the different industries require access to a set of limited resources (namely, WWTP's flow capacity and contaminants levels). Moreover, the flexibility of the industries to change their discharge times is very low. Actually, it could be seen as having no flexibility at all, since the discharges are generated by a production process that cannot be stopped. However, there must be some way of containing a discharge if it cannot be performed at a given time. To this end, industries can store the produced waste in a retention tank, instead of directly putting it into the sewage system. This retention tank should give enough margin to distribute the actual discharges without having to modify the industries' productivity, while coordinating their discharges with the other industries.

Note that the problem is not to reorder the discharges of each industry, but to find the sequence of resource use (i.e. allow an industry to perform a discharge or oblige it to store it in its tank). This sequence should ensure that the plant's thresholds are not exceeded, and also that the industries can perform their planned discharges, so that their tanks do not get completely filled.

To solve this scheduling problem, we could opt for a centralized approach (for example as in [3]), which given all the discharges information generates a new schedule for each of the industries, without any conflicts between simultaneous discharges or at least minimizing their hazardous effects. Such a centralized approach implies that the central scheduler would made all the decisions (whether to discharge or use the tank). 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, we have chosen to use a distributed approach for coordinating the schedules. Moreover, having in mind the distributed nature of the scenario, we have designed it as a Multiagent System. Thus, there is an agent representing the plant (the *WWTP agent*), and one agent for each of the discharging industries (the *industry agents*). As for the coordination method, we propose to use an auction-based mechanism, which is widely used in resource allocation problems with privacy issues [1], and we believe that it can also be applied to the schedule coordination problem.

The coordination mechanism works as follows. Firstly, the industries inform the WWTP agent about their discharge schedules, which contain the set of discharges (starting time, duration, flow and contaminants levels) each industry plans to perform in a given period of time. Then the WWTP agent starts checking for conflicts (i.e. whether the plant's thresholds are exceeded). When a conflict is detected, the involved industry agents are informed about it, and an auction is started in order to select which industries will be authorized to discharge. Once the auction is completed, the industry agents are informed about the result, which can then modify the rest of their schedules (in the case the industry has not been authorized to discharge). This process is repeated until all the discharges have been authorized, and the result is that each industry has a new discharge schedule. The coordination is done off-line, that is, a few

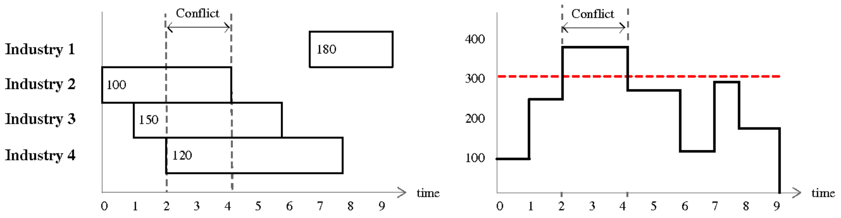

Fig. 1. Conflict example. Discharge plans (left) and accumulated flow (right)

days before the actual discharges take place. Next we describe in more detail the two main points of the coordination process: *conflict detection* and *conflict resolution*.

3.1 Conflict detection

Given each discharge being described as $D_i = \{industry\_id_i, s_i, d_i, q_i, \overline{c}_i\}$, where s_i and d_i are the starting time and duration of the discharge, and q_i and $\overline{c}_i$ are the flow and contaminants levels of the discharge, and the set of active discharges at time t is $AD(t) = \{D_i | t \in [s_i, s_i + d_i]\}$, a conflict arises if any of the following two restrictions is violated:

$$\sum_{i=1}^{|AD(t)|} q_i \leq Q \quad \text{(hydraulic constraint)}$$

$$\frac{\sum_{i=1}^{|AD(t)|} q_i \cdot \overline{c}_i}{\sum_{i=1}^{|AD(t)|} q_i} \leq \overline{C} \quad \text{(contamination constraint)}$$

where Q is the WWTP hydraulic capacity and $\overline{C}$ is the vector with the contaminants thresholds of the WWTP.

When one of the above conditions is broken, a conflict is detected. At this point, all the industries that were performing a discharge are considered to be involved in the conflict. The starting point of the conflict is the starting time of the discharge that first causes one of the conditions to be violated. The end point of the conflict is set to the time when an industry finishes a discharge and causes the conditions to be met again.

Figure 1 illustrates an example of conflict detection, with four industries discharging waste with different flows (shown in the left). For example, in timestep 0, the second industry begins to discharge with a flow of 100 m^3/d, finishing at timestep 4 (so, $AD(0) = \{(I2, 0, 4, 100)\}$; for clarity's sake, we do not show the contaminants levels). The right part of the figure shows the accumulation of discharges. Supposing that the hydraulic capacity of the WWTP is 300 m^3/d (depicted in dashed line in the right figure), a conflict arises at timestep 2, when industry 4 starts its discharge. At this time, $AD(2) = \{(I2, 0, 4, 100), (I3, 1, 5, 150),$ $(I4, 2, 6, 120)\}$, and the sum of flows being discharged by the industries (370) exceeds this limit. The conflict ends at timestep 4, when industry 2 finishes its discharge and the sum of the remaining flows (270) falls below the capacity threshold. In this case, the involved industries in the conflict are $I2$, $I3$ and $I4$.

3.2 Conflict resolution

As discussed earlier, we have decided to use an auction mechanism to mediate the conflicts between the industries. Once the involved industries have been detected, their corresponding agents are informed about the conflict and the auction process begins. The goal of the process is to select a subset of industries, which will be authorized to perform their discharges. The remaining industries should use their tanks to retain the planned discharges.

The selection criteria is based in the industries' bids. These bids represent the urgency each of the industries has to perform the discharge. A high bid indicates that the industry really needs (or wants) to discharge, while a low bid indicates that the industry could retain its discharge in the tank and therefore it can miss the opportunity to perform it at the auctioned time.

Formally, the problem to solve by the WWTP agent (known as the *winner determination* or *auction clearing* problem) is similar to a multi-unit combinatorial auction [4] or a multi-dimensional knapsack problem [5]:

$$\max \sum_{i=1}^{ND} x_i \cdot v_i \qquad \text{s.t.} \qquad \begin{array}{c} \displaystyle\sum_{i=1}^{ND} x_i \cdot q_i \leq Q \\ \dfrac{\sum_{i=1}^{ND} x_i \cdot q_i \cdot \overline{c}_i}{\sum_{i=1}^{ND} x_i \cdot q_i} \leq \overline{C} \end{array}$$

where:

- ND is the number of conflicting discharges,
- $x_i \in \{0,1\}$ represents whether discharge i is denied or authorized,
- $v_i \in I\!R^+$ is the bid value for discharge i,
- and q_i, $\overline{c}_i$, Q and $\overline{C}$ are the discharge and plant characteristics

The auction process is repeated every time a new conflict is detected. This leads to a *recurrent auction*, where the same bidders (the industries) are continuously competing for the same resources. This kind of auctions have received little attention, but they are gaining importance, since there are many applications where this recurrence takes place (such as in e-services marketplaces). One of the main concerns in recurrent auctions is to keep the agents interested in participating in the auction. If only a small subset of the agents are winning the auctions, the rest of the agents may decide to leave the marketplace since they are not getting any benefit, in what is known as the *bidder drop problem*. This can have important drawbacks, be them economical (in an e-service scenario) or diminishing system performance (in a coordination scenario). In the former, the decrease in product demand could imply a decrease in the product's price, which would decrease the auctioneer's profit, thus collapsing the market. In coordination, it can cause the agents to stop obeying the outcome of the coordination and start behaving on its own, which could conflict with the behavior of the agents agreeing with the coordination.

4 Adding Fairness

To avoid, or somehow decrease, the bidder drop problem, the recurrent auction process should have some degree of fairness, so that any agent has some possibility of winning from time to time. This would keep the agents attracted in taking part of the auction, which would benefit the performance of the system. The inclusion of fairness can be somewhat acting against optimality, since the result of an auction may differ from the optimal solution if a suboptimal solution is fairer. However, its long-term effect can have a better performance than a pure utilitarian view, since the duration of the recurrent auction may be longer with satisfied agents and the final outcome could be much higher. Moreover, an immediate effect of fairness when using the recurrent auction for coordinating schedules would result in the original schedule of the agents to be modified the least possible, which is very important when dealing with selfish agents.

There are many ways in which fairness could be introduced into the auction. We have chosen to use a priority mechanism that takes into account the history of each agent in previous auctions. Each agent is assigned a priority value depending on the number of won auctions (in our domain this would be the number of authorized discharges) and lost auctions (number of denied discharges). A high priority value indicates that the agent should be authorized to discharge, since there is some danger of the agent disobeying. Conversely, a low priority value indicates that it would not be unfair to deny a discharge to a given agent.

The priority values are updated after each auction is finished, and they are used for clearing the next auction. The clearing algorithm could use them in very different ways: they could be transformed into new constraints to be satisfied by the solution, or directly designate the set of winning agents, among others. We have decided to use the priorities as a modifier of the bids sent by the agents. More precisely, given a bid v_i of an agent with priority w_i, a new bid value is computed as $v'_i = f(v_i, w_i)$. This new value is the one used for the clearing algorithm to find the solution to the auction. The function f can also be designed in many ways, and it defines how much the fairness affects the auction solution.

5 Experimental Results

To evaluate the coordination mechanism we have implemented a prototype of the system, using Repast[1], a free open source software framework for creating agent based simulations using the Java language. As a first evaluation step, we have only considered the hydraulic capacity. Due to lack of space we can only briefly mention the implementation details (see [6] for more details): the bid computation is based on the occupation of the retention tank of each industry; the priorities are computed as the percentage of lost auctions over the total number of auctions an agent has participated in; and finally, the function to

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[1] REPAST Agent Simulation Toolkit, http://repast.sourceforge.net

		NO	MFO	VO	TDT	%A	%MWA	%IO	%IDF	%IDT
w/o coord		8 (1.94)	8015 (2069.36)	$2.5 \cdot 10^6$ $(0.8 \cdot 10^6)$	—	—	—	—	—	—
Obeying	w/o prios	2.8 (1.55)	3780 (2650.81)	7655 (6611.92)	346.32 (93.03)	80.16 (31.51)	11.65 (12.82)	58.013 (15.13)	—	41.99 (15.13)
	w/ prios	1.9 (1.91)	2545 (2097.15)	5020 (5336.94)	318.24 (99.25)	78.72 (23.23)	35.35 (20.36)	70.38 (21.24)	—	29.62 (21.24)
Disobey	w/o prios	3.5 (2.22)	3780 (2650.80)	9505 (8359.44)	334.2 (84.62)	82.39 (30.14)	11.92 (14.09)	19.09 (30.54)	79.95 (30.47)	0.96 (0.80)
	w/ prios	2.6 (2.79)	2545 (2097.14)	6370 (7156.82)	303.24 (93.32)	79.62 (23.19)	34.15 (18.50)	46.27 (41.23)	52.26 (40.71)	1.48 (1.54)

Table 1. Experimental results (average and standard deviation)

modify a bid depending on the priority is $v'_i = v_i \cdot w_i$. The linear programming toolkit GLPK [2] has been used to solve the winner determination problem.

We have tested the system in three different scenarios. In the first scenario there is no coordination among the industries. The second one uses the coordination mechanism and assumes that the industries always obey the WWTP decisions, as long as they have enough tank capacity. The third scenario has coordination and we introduce a probability to disobey the outcome of the coordination mechanism. This probability depends on the occupation of the tank (the higher the occupation, the higher the chances of disobeying). The two scenarios with coordination have been tested with and without priorities.

In order to evaluate the system we have considered some quality measures based on different characteristics of the solution:

- **number of overflows (NO)** occurred during the execution of the schedules.
- **maximum flow overflowed (MFO)**, measured in m^3/d.
- **total volume overflowed (VO)**, in liters.
- **difference between the final time of the execution with coordination and without coordination (TDT)**, in minutes.
- **percentage of conflicting discharges that have been authorized (%A)**.
- **minimum percentage of won auctions (%MWA)** among all agents.
- percentage of discharge denials being **obeyed** by the industries **(%IO)**.
- percentage of discharge denials **disobeyed due to the disobey function (%IDF)**.
- percentage of discharge denials **disobeyed because the industries' tanks were full (%IDT)**.

The experiments consisted of ten simulations using a set of real data of ten industries in ten different days. The industries can have the same discharge schedule each day (if they produce the same products every day) or different

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[2] GNU Linear Programming Kit, http://www.gnu.org/software/glpk

(if they have changes in the production process). The hydraulic capacity of the WWTP is 6500 m^3/day.

Table 1 shows the average and standard deviation of the ten executions. The differences between TDT and %A when using priorities and without them are not statistically significant in any of the scenarios. However, the difference in %MWA is statistically significant in all the scenarios.

The results show that with schedule coordination the number of overflows (NO), the maximum flow overflowed (MFO) and the volume overflowed (VO) are drastically reduced (note the three orders of magnitude reduction in volume overflowed). Moreover, with priorities the reduction is even higher. Regarding the %IO, %IDF and %IDT measures, it is noticeable that with priorities the obedience (%IO) is significantly increased in all scenarios. In addition it is interesting to comment that in the third scenario, with disobedient industries, the system performance is very similar than in the second one, with obedient industries. Also note that in the scenario were disobedience is allowed, the use of priorities reduces the percentage of industry disobedience. This means that priorities add robustness to the coordination mechanism.

Regarding the rate of authorized discharges (%A), the percentages obtained with or without priorities are similar. However, the standard deviation in each of the experiments is smaller when using priorities. Actually, the average of this standard deviation is about 30% without priorities, and about 23% with priorities. This means that the difference between the agents is reduced with the use of priorities, increasing the fairness of the system and avoiding the bidder drop problem. Moreover, the results also show that the minimum percentage of won auctions (%MWA) is significantly increased with priorities (which is about 34%, against 12% when priorities are not used, as shown in Table 1). This indicates that an agent has more chances of being authorized to discharge when the priority mechanism is used.

The drawback of the coordination mechanism is that the final time of the execution (TDT) is increased. This could cause some problems with the scheduling of the following day. Although this delay is considerable, the effect of priorities and its fair distribution can be seen in the reduction of the average and standard deviation of this time. If an industry were allowed to perform simultaneous discharges (from the tank and from the production process), the reschedule delays could be shortened. We need to deal with this possibility in future work.

6 Related Work

There are many approaches to handle schedule coordination: use a divide-and-conquer strategy [7, 8], solve it as a constraint optimization problem [9], or use auctions [10, 11], among others. We have followed the latter option, use a market-approach to coordinate the schedules. The characteristics of our problem makes the auction to be continuously repeated, thus dealing with a recurrent auction. This kind of auction is recently being used for e-services markets, such as assigning advertising time in public displays [12] or in networking markets [13].

This latter work is closely related to our problem, since it tackles the bidder drop problem. We are also very interested in this problem, since we need to incentivize the agents to participate in the coordination process. In [13] the problem is solved by defining a more flexible winner determination algorithm, which takes into account the bidder's outcome history in past auctions. The goal of their work is to incentivize the bidders to stay in the market place, so that the prices do not collapse. We also use this history in order to compute the agents' priorities, however our objective is not economic but to obtain a fair distribution of the discharge authorizations.

Regarding work on water treatment systems, there has been much research on the internal treatment processes, but very little on coordinating the different systems involved. In [14] a negotiation approach to coordinate different WWTPs treating the same river basin is presented. However, the elements being coordinated in this work are the plants, leaving the industries aside.

7 Conclusions and Future Work

In this paper we have presented a mechanism to coordinate schedules that have already been generated by selfish agents competing for a set of limited resources. Through the coordination, the individual schedules are refined whenever a conflicting situation is detected. The new schedules contain a sequence of resource use that is distributed over time and decrease the risk of possible system failures (i.e. resource overuse). The core of the coordination mechanism is a recurrent auction, in which agents can bid for the right to use a resource at a given time.

The auction has been extended with a priority mechanism to introduce fairness in the assignment of resources. With this mechanism, the assignments are evenly distributed among the agents, meaning that their original schedules are modified the least possible. This is a very desirable property of a coordination mechanism, since it incentivizes agents to participate in it. Otherwise, if the mechanism were to drastically modify their schedules, agents would be reluctant to participate. This could lead to an overall failure of the system, since each agent would be acting on its own. This is specially important in environments where agents are self-interested and do not pursue a common goal.

We have applied the mechanism to a waste water treatment system. In this scenario, different industries compete for performing waste discharges that have to be treated by the plant. The results obtained through simulation show that the coordination mechanism achieves the goal of maintaining the incoming flow below the WWTP hydraulic threshold. The results also show that the use of priorities provides a fairer solution of the auctions. Moreover, we have shown that these priorities add robustness to the solution, since even when the industries do not comply with the outcome of the coordination process, the overall system performance is not drastically affected. However, we need to further study how to reduce the delay produced by rescheduling.

As future work, we need to experiment with the contaminants levels restriction, since we have taken into account only the hydraulic capacity of the plant in the current prototype. We also plan to incorporate a more economical view of the bidding process (including bills and penalties), and also to deal with incentive compatibility issues. Finally, we should compare the performance of our mechanism with a centralized approach.

8 Acknowledgments

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