A Multi Agent-based Approach for Energy Efficient Water Resource Management

Mehmet Emin Aydin[a,1,b], Rustem Keles[b,1]

[a] *Dept. of Computer Science and Creative Technologies, Universoty of the West of England, Bristol, UK*

[b] *Secretariat General, Metropolitan Municipality, Kahramanmaraş, Turkey*

Abstract

Water supply remains one of globally recognised challenging problems due to the scarcity in the water sources, the environmental concerns and hardness in access to clean and fresh water. Besides, energy consumption is also under focus as much as access to fresh water is. Substantial research efforts have been spent to produce good solutions for each of these global problems. However, there is not much investigated on considering both issues together in the same problems structure. This paper focuses on efficient planning and control of water supply in a middle-size water-rich city using a multi-agent approach to handle the problem with respect to a number of key performance indicators including energy efficiency, given a variety of water resources including constructed and natural reservoirs. A particular case scenario is considered and its mathematical model is developed in order to optimally plan and control fresh water supply to the metropolitan area of the city introduced in the scenario. The multi agent system has been used for production control of untreated water from different water resources. The evaluations have been done through episodes and the results are encouraging.

Keywords:
Energy Efficiency, Water Resource Management, Mathematical Programming, Multi Agent Systems

---

Email addresses: `mehmet.aydin@uwe.ac.uk` (Mehmet Emin Aydin), `rustemkeles@kahramanmaras.bel.tr` (Rustem Keles)

Preprint submitted to Computers & Indistrial Engineering *July 18, 2020*

1. Introduction

Water resource management remains as one of the prominent activities in the modern urban life to sufficiently supply and distribute fresh and clean water. The issues in this regard attract lots of research attention and investigations over the years. Clean and fresh water supply is recognised as one of the global issues under the focus of United Nations across the globe due to the fact that very large populations live in difficulties to access clean and fresh water to drink and for sanitation purposes, while the wasted volume of natural water resources are substantially solid [1]. This obliges to optimise use of water resources and efficiency in supply subject to the needs and cleanness. A number of studies have been carried out to optimise water supply systems with various respects [2, 3]. Water resource management is not a new subject, which has been studied for long time, however, it still takes so much attention due to the scarcity of fresh water resources, and environmental challenges. Works have been done considering more integral views and changing circumstance [4, 5, 6, 7]. Researchers keep investigating new approaches and studying for better solutions and further performance enhancements taking many issues and requirements into account from all stakeholders, whom were not counted before [2, 3, 8]. That enforces use of new technologies, e.g. internet of things (IoT) and artificial intelligence (AI), and the ever-growing computing power for higher efficiency in supply, delivery and management.

Energy efficiency and power consumption are another two very important issues, globally under focus, and attracts significant attention. The long term cost of natural resources for power generation and the scarcity in power resources oblige energy saving and efficiently use similar to fresh water cases. It is known that a number of water resources can help generate hydro-electric power without harming water quality with respect to cleanness. Although a number of studies have undergone to investigate for better water supply and management systems, none of them have considered power generation and water supply in the same problem structure, to the best knowledge of the authors. This paper extends the idea presented in [9] that proposed an optimisation model for water supply planning and a multi agent system for control as part of water resource management.

The rest of the paper is organised as follows: Section 2 introduces water resource management in general following with a optimum planning and control models for water production and distribution. Section 3 presents the corresponding methods and materials including a multi agent system proposed for water production control as part of water resource management, Section 4 provides the details of numerical experimentation and discussions, while Section 5 provides the final conclusions.

2. Background

This study attempts to apply multi agent systems as one of cutting-edge AI technologies to water resource management, which is one of outstanding and prominent real-world problem. It covers mainly update of water resource management and a particular hypothetical case with energy efficiency in mind. The following subsections overviews relevant subjects accordingly.

2.1. Water Resource Management

Water resource management involves all levels of enterprise/corporate management including strategic, tactic and operational levels. The scope of this paper is limited to operational level, where interaction with tactic level is reasonably frequent. The activities in operational level are handled in two stages; the planning and control stages. The research reported in this paper mainly focuses on both planning and control functions in water resource management extending the study reported in [9]. The planning function is handled with a pre-developed mathematical models to optimise water supply and feed these results into the control functions, where a multi agent system is proposed to manage all control activities.

A number of recent researches have paid attention on comprehensive approaches to resolve the issues around water resource management, with all relevant aspects, within a larger enterprise scope. A broad literature review on water resource planning using evolutionary computation is provided in [10], while [4] and [5] widely discuss a comprehensively integrated system for water resource management and optimisation. [6] proposes an integrated approach for solving the same problem for a particular metropolitan area of a Chinese city. Similarly, [7] introduce an approach for Peru. The main difference between these works and this study is the role of energy efficiency and power generation within the problem structure. We propose this approach with the vision of water resources optimisation together with power generation and use. The water resource sharing among multiple major users has been modelled and studied by [11] in which sustainability, sufficiency and the way of corporation have been considered in the planning model. The involvement of many geographical sites and compulsory collaboration, one of state-of-art technologies, internet of things ([12]) extended with multi agent modelling [13, 14], has been considered in this study. The main motivation behind this idea is to furnish the nodes of IoT system with intelligent components so that the developed bespoke IoT model can be as decisive and timely as possible for high efficiency in performance. Multi agent systems were used to model water resource management systems in various respects [15]. [16] have proposed a game-theoretic multi agent system for optimisation of water resource allocation. [8] introduces a water allocation system modelled and optimised as a multi-objective optimisation problem. A very similar approach is implemented by [17] to solve water management problems modelled as distributed constraint satisfaction problem using a multi-agent system approach. [18] provides a nice review on use of mathematical programming for water resource management under uncertainty. There has not been any study conducted planning and control of supplying water from multiple resources that have different water characteristics using multi agent systems.

Water supply service is fulfilled in two phases as explained before; *planning* phase in which the amount of water is planned to production for supply and *control* phase, which is about the distribution through the urban pipeline network. The planning (water production) phase involves extracting water from the sources, processing it to a usable quality and pumping to corresponding water towers. The control (water distribution) phase is all about supplying water from corresponding water tower to final destination.

2.2. Planning for water production

Water production process mainly involves with extracting water from resources, e.g. lakes, dams, wheels etc., and processing it to a usable quality for domestic use in household. The production process with all involvements is a planning process in which the demanded water for domestic use is required to be made available in desired level of quality, hence, it turns to a constrained optimisation problem. A metropolitan area is supplied with produced water from N number of water resources/reservoirs, which have offer unprocessed water in different qualities. Let $\mathbf{x}_t = \{x_{t,n} | n = 1..N\}$ be the vector of real values representing the water volumes extracted from N resources at time t, the time index within the time period of T. $t \in T$. The cost that incurs to produce $\mathbf{x}_t$ is $\mathbf{c}_t = \{c_{t,n} | n = 1..N\}$, which is the vector of unit cost $c_{t,n}$ to extract $x_{t,n}$ volume and process it to supply via a water tower. This process repeats independently for each water tower, hence, it is not considered as a dependent or independent variable. The total cost of water production is aimed to be minimised with an objective function as follows:

$$Z_p = \sum_{t=1}^{T} \sum_{n=1}^{N} c_{t,n} x_{t,n} \tag{1}$$

The production cost per unit of water volume covers pumping and cleaning (processing) operations denoted with $c^p_{t,n}$ and $c^c_{t,n}$, respectively. We are aware that some water resources are constructed dams in which power generation can be achieved whilst water extraction, which can help reduce the production cost per unit of water volume. Then, another cost item, $c^g_{t,n}$ should be considered within costing operation. The final cost per volume can be calculated with $c_{t,n} = c^c_{t,n} + c^p_{t,n} - c^g_{t,n}$. Here, $c^g_{t,n}$ is an approximate quantity estimated through a function $f(e_{t,n})$ which can be customised subject to the circumstances, where $e_{t,n}$ is the amount of power produced from falling water from resource n, e.g. a constructed dam, at time t, and can be calculated using an energy function such as $g(x_{t,n})$, which can be detailed from power generation processes. The total produced water should be sufficient to meet the demand, D_t, at time, t.

$$\sum_{n=1}^{N} x_{t,n} \geq D_t \quad \forall t \in T \tag{2}$$

It is known that each water resource, n, has a particular capacity, which is identified with upper and lower boundaries, $\lambda_{min,n}$ and $\lambda_{max,n}$. Water can only be extracted from resource n, if the water level, $l_{t,n}$, is above the lower boundary as follows:

$$x_{t,n} = \begin{cases} 0, & l_{t,n} \leq \lambda_{min,n} \\ x_{t,n}, & \text{otherwise.} \end{cases} \quad \forall n \in N \quad \forall t \in T \tag{3}$$

The water level is dynamically updated with detailed models in hydraulics, but, it is, here,approximately estimated with $l_{t,n} = l_{t-1,n} + \Phi$, where Φ represents the natural water accumulation per water source. Finally, each water resource brings its own quality parameters, which play important role in water production process. The prominent quality parameters can be muddiness of the water, $\mu_{t,n}$, the pH level, $\rho_{t,n}$ and other cleanness parameters, $\emptyset$, need to be taken care for an acceptable quality level $q_{n,t}$, i.e. quality of water extracted from resource n at time t, for the water to be consumed domestically. On these basis, a quality index can be estimated with

$q_{n,t} = w_\mu \mu_{t,n} \oplus w_\rho \rho_{t,n} \oplus w_\emptyset \emptyset$, where $\mathbf{w} = \{w_i | i = \mu, \rho..\emptyset\}$ can be the weights to normalise the relation and $\oplus$ is an operation to compose all relevant terms into the quality index, which can be customised based on the expert knowledge and environmental circumstances. A threshold of quality, say Ω, needs not to be exceeded per unit of produced water volume. Here, the quality should be applied to water volumes extracted from all water sources as follows:

$$\sum_{n=1}^{N} \frac{q_{t,n}}{x_{t,n}} \geq \Omega \quad \forall t \in T \tag{4}$$

Eq.4 imposes an nonlinear property to this model, which is required to be linearised if linear programming approaches would be used to solve the problems implemented with this framework.

This set of equations (Eq.1 - Eq.4) can be pulled together to make up the mathematical model for planning water production as in the set of equations (Eq.5). The aim is to optimise water volume extracted from different types of reservoirs, such as natural lakes, constructed reservoirs (dams), to supply in the metropolitan area of a city. It integrates water production and supply problem with energy efficiency bringing the impact of energy into the water production process through cost coefficients. Here, it is assumed that the power generation is separately handled and the results are fed into the model in costing form. Optionally, the energy can be co-optimised alongside water production and supply using multiple objective optimisation models, but, this will impose considering many other factors, which would enforce to ignore the priorities of this study.

This model is aimed to be used for planning purposes and, hence, considers discrete data flow over the periods of time, e.g. days, weeks or months. The quality of the water to be supplied requires to be over a particular level for health and safety concerns (regulations), while the cost of supply varies due to reservoirs circumstances. Therefore, the volume of water to be supplied is required to be a mixture from different resources, where the quality level and pumping costs need to be optimised.

Minimise

$$Z^p = \sum_{t=1}^{T}\sum_{n=1}^{N} c_{t,n}x_{t,n} \tag{5}$$

Subject to:

$$\sum_{n=1}^{N} x_{t,n} \geq D_t \quad \forall t \in T$$

$$x_{t,n} = \begin{cases} 0, & l_{t,n} \leq \lambda_{min,n} \\ x_{t,n}, & \text{otherwise.} \end{cases} \quad \forall n \in N \quad \forall t \in T$$

$$\sum_{n=1}^{N} \frac{\omega_{t,n}}{x_{t,n}} \geq \Omega \quad \forall t \in T$$

$$x_{t,n} \in \mathbb{R}$$

Production planning model offers a flexible water production plans in master level for targeted time period through episodes. The framework is kept flexible and adaptive for time periods, where T can be counted on a daily, weekly, monthly or seasonal basis. This feature makes it easier to plan according to time sensitivity. On the other hand, with N, the number of resources is kept flexible and new resources can be included in the planning at any time. In the model, the distribution centre is assumed to be made from a single location. If there is more than one distribution warehouse, there will be a variety in costing and a change of model will be needed.

2.3. Optimisation for distribution

Planning model for water production does not consider suburban demands and distribution aspects, but aims water production for the overall metropolitan area. The corresponding distribution can be modelled as capacitated p-median problem due to the logistic nature of the problem, where the entire metropolitan area would be supplied with clean and fresh water through a wide-area pipeline serving from multiple water towers.

Let P be the number of water towers serving to the entire metropolitan/urban area and M be the number of customers put demand forward.

Each customer i will be served with $y_{i,j}$ amount of water from tower j through the water distribution pipeline, which incurs $c_{i,j}$ per unit of water volume. It is important to note that a capacity is imposed per water tower, K_j, and each customer puts a demand, d_i forward. The aim is to minimise the cost of supplying the demanded water volume within the time window that the demand is requested for.

$$Z_t^d = \sum_{i=1}^{M} \sum_{j=1}^{P} c_{i,j} y_{t,i,j} \quad \forall t \in T \tag{6}$$

where the total distribution cost over the time period T will be $Z_d = \sum_{t \in T} Z_t^d$ to be considered as the final objective function of distribution model.

The demand by each customer is ensured to be met with the constraint of $\sum_{j \in P} y_{i,j} \geq d_i$, $\forall i \in M$, while to be conscious of the capacity of each water tower with $\sum_{i \in M} y_{i,j} \leq K_j$, $\forall j \in P$. This model is developed per time window, which is applied to water production model. In order to run the minimisation model with time in mind, the objective function and the constraints need to add another dimension to the variables accordingly; mainly, the decision variable for water amount will be $y_{i,j,t}$ and the demand per customer will be $d_{i,t}$, where the demand considered in production model will be broken into portions per customer, $D_t = \sum_{i \in M} d_{t,i}$ $\forall t \in T$. It is paramount to note that the demanded water volume per customer, $d_{t,i}$, can only be successfully delivered if it remains within the infrastructure capacity of distribution pipeline per time episode. In this study, we assumed that the pipeline capacity is always available.

$$\begin{aligned} &\textbf{Minimise} \\ Z^d &= \sum_{t=1}^{T} \sum_{i=1}^{M} \sum_{j=1}^{P} c_{i,j} y_{t,i,j} && (7) \\ &\textbf{Subject to} \\ \sum_{j \in P} y_{t,i,j} &\geq d_{t,i}, \quad \forall i \in M \text{ and } \forall t \in T && (8) \\ \sum_{i \in M} y_{t,i,j} &\leq K_j, \quad \forall j \in P \text{ and } \forall t \in T && (9) \\ y_{t,i,j} &\in \mathbb{R} \quad \forall t \in T && (10) \end{aligned}$$

Although the model does not look exactly like a classical capacitated p-median problem, it can easily be converted into transforming the real decision variables into binary ones and releasing the model form the time-window constraints.

The production and distribution models are set up and run separately, despite that both are minimising cost. The total cost of operation can be estimated with the simple sum of optimised objective function values, $Z_{overall} = Z_p + Z_d$, although it is not a good idea to combine the both optimisation models into a single due to easing complexity.

3. Methods and Materials

The control stage of water resource management is about running the management system in real time for delivering the required services. Planning stage helps develop master plans for water supply and use of resources efficiently. That is the starting step for control stage. In order to control the water supply whether the water quality is appropriate and if there is any way of better delivery, a multi agent system is proposed in this paper, where a number of autonomous agents collaborate towards running the systems as efficient as possible. The motivation behind proposing a multi agent system is that the success in use of multi agent systems in various other problem-solving purposes ([19], [20]), and running real-time control systems successfully ([21]).

3.1. Multi agent system for production control

The proposed approach for the purpose of controlling water resource management is sketched in Figure 1. First of all, the logic presented in the figure is implemented into a model of internet-of-things (IoT), where a network of sensors equipped and arranged for real-time data flow and exchange. Then, each node of IoT is converted into an autonomous agent with adding components to the nodes to produce intelligent behaviours. The reason to do this is to set up an intelligent cooperative system, which can deliver more than what an IoT system can do. A good example for use of IoT in water resource management can be seen in [22].

The architecture of the whole water resource management system is provided in Figure 1, where an IoT application equipped with multi-agents turns into a network of smart devices, may also be called as Internet-of-Smart-Things (IoST). Each node of the network, (e.g. IoST), is an autonomous agent, which represented into pentagons and hexagons. The operative agents

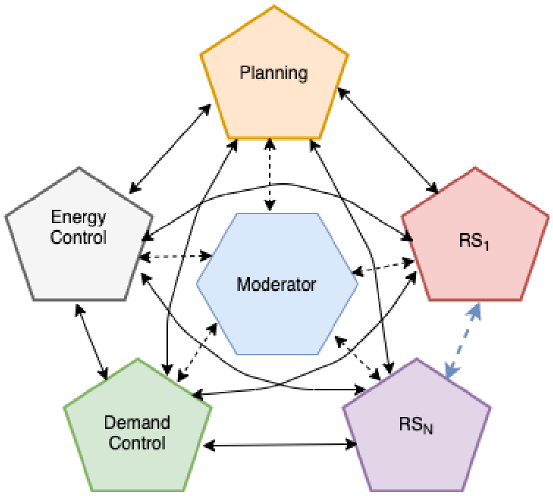


Figure 1: The proposed multi-agent architecture to handle water resource management

- Planning, RS$_1$, RS$_N$, Demand Control, Energy Control- are in shape of pentagons, while only Moderator is in hexagon for differentiation purpose. The dashed connector in between RS$_1$ and RS$_N$ represents the possibility of more resources to take part in the water production system, where each to be represented with RS$_i$.

A communication protocol is required to be installed as the media for agent communication in which each individual agent would be allowed to have interaction with any peer agent within the team. There is not any central control imposed upon the whole system in which autonomous agents are capable of one-to-one connection. This means that each agent is allowed to communicate with every other single agent subject to the need of information and knowledge to exchange. It can be noticed that the communication among operative agents is depicted with solid arrows, while with dashed arrows for moderator agent. The agents are furnished with all required capabilities; sensing information from the environment, communicating with other peer agents, deliberating and concluding knowledge, decision-making and actuating upon decisions made. The operative agents need to be devised with different capabilities subject to the roles taken up.

Autonomy is one of the most important characteristics of agent-based systems in which proactiveness of agents is maintained for required intelligence and collaborative behaviour. The agents will remain listening the system and other peer agents for stimulus to act upon. The autonomy of operator

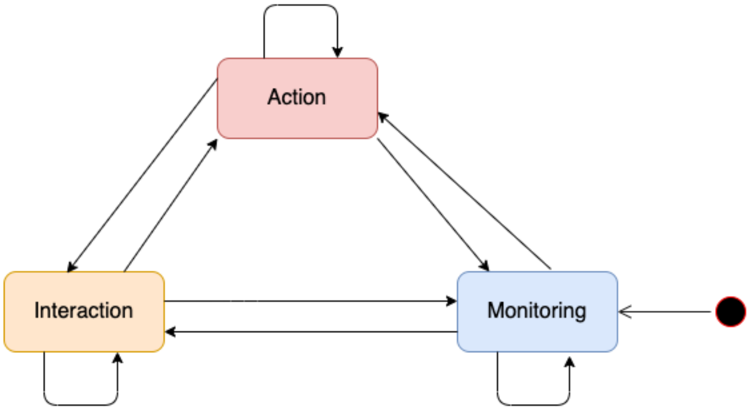


Figure 2: A state machine diagram for autonomy

agents is presented in Figure 2, where autonomous behaviour of an agent on each node is devised with a finite state machine using 3 states; *action*, *interaction* and *monitoring*. Transition between any two states are triggered with the stimulus captured from the environment, where an agent initially remains on *monitoring* state unless it receives a triggering message to move to *action* state. The *action* state is to fulfil the duties, which are the agent designed for, where each agent is devised with a number of functionalities to take actions for delivering the duties. Both monitoring and interaction states are two special states in which the agents fulfil (i) monitoring the environment and the other fellow agents, and (ii) interacting with other fellow agents to agree on collective behaviours. Transition from *monitoring* state to *interaction* state without going through *action* state. Meanwhile, if the task allocated to the agent requires interaction with other agents, the *action* state will let it transit to *interaction*. The transition back to original state, either *action* or *monitoring* state will happen once the communication is completed. As seen in Figure 2, the agent will move back to *monitoring* state upon the complete of duty fulfilment. All emergency alerts will come through *monitoring* state triggering *interaction* and *action* states to run the emergency action specified for each peer agent.

3.2. A Water Supply Scenario

In this scenario, a hypothetical company is assumed to be in charge of water supply in a medium-size metropolitan area, where a number of water resources are used to supply clean water in a certain quality to the urban

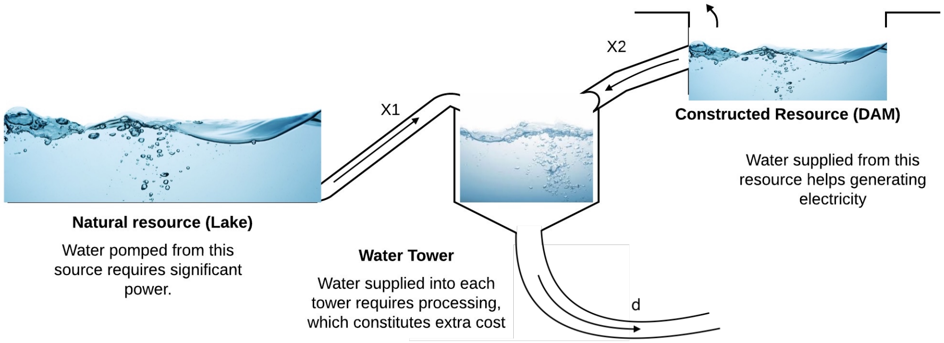


Figure 3: Water supply scenario

area within corresponding metropolitan region. XYZ Co. is the company in charge of water supply and sewage management of the metropolitan municipality of the region. The company manages distribution infrastructure and aims to increase efficiency of energy control throughout a project. The scenario has been sketched out in Figure 3, where a water tower is supplied with two reservoirs; a natural lake (Lake), and a constructed dam (DAM). It is known that Lake has been used as the main water resource for the metropolitan area to this day, but, it is also known that it cannot afford the growing volume of the demand. This enforces the company to invest in constructing new reservoirs on the river passing by the metropolitan area being conscious about the quality of the water with respect to cleanness and sanitation requirements imposed by public standards. The new reservoir (DAM) commissioned by the company is expected to supply more water to be consumed within the urban area for any kind of domestic use. The water quality is known to be much preferable due to contained minerals and organic/inorganic pollutants. DAM is also planned to generate power through a hydro-power plant (HPP), which can be used for production and distribution process of water supply; from resources to the towers and from towers to the final destinations. Meanwhile, it is known that water supply from Lake requires extracting from the bottom of the lake, which consumes a substantial amount of power.

The resource planning and optimisation for described case in the scenario would be implemented in two stages; in the first stage, the water supply will be planned through the optimisation model for planning purposes, while in the second stage the real delivery of water supply will be controlled, accordingly. The control model is developed based on an internet-of-things model extended with intelligent components, and hence, converted in a multi-agent system to function in real time.

3.3. MAS implementation for water production process

The collaborative behaviour from a multi agent system is the outcome of a well-established interaction and collaboration among the team of agents. As planned and sketched in the architectural diagram (Figure 1), the entire system is designed to build collaboration among the operational agents. An implementation of coordination among the agents is shown in Figure 4, where the operational agents only take role, no-mediator agent is recruited.

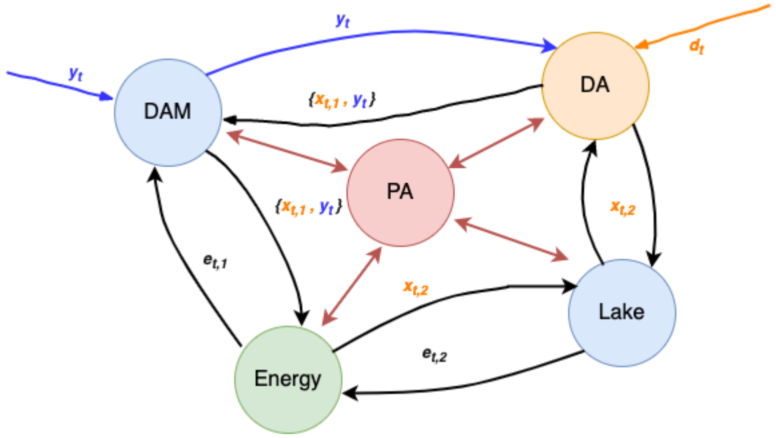


Figure 4: Agents interaction

Figure 4 presents two typical stimulus triggering water resource management system; the system is actuated with d_t amount of demand for the time being through Demand agent (DA), where DA organises the demand requests communicating with planning agent (PA) for using existing plans to run. PA evaluates incoming information, upon receiving the messages from DA, matching the original optimum plan with the current circumstances, benchmarking the quality levels, and checking the available capacities of the resources to decide the volumes of water to be supplied from each resource. Since there are only two resources considered in this study, $x_{t,1}$ and $x_{t,2}$ volumes are requested from DAM and Lake agents, respectively, being mindful that DAM is to produce power, $e_{t,1}$, and Lake is to consume power, $e_{t,2}$, while supplying the allocated water volumes. Both of these energy quantities are used in calculating the costs of water supply as explained in Section 2.2 and supplied into objective function, Eq. (1).

Table 1: Information exchange between two communication agents to handle water production process per time period

Requesting Agent	**Responding Agent**	**Request**	**Response**
DA	PA	Demand, d_t, Quality Reqs. including Ω	Volumes, $x_{t,n}$, Quality parameters, $\{q_{t,n}, \mathbf{w}, \mu_{\mathbf{t,n}}, \rho_{\mathbf{t,n}}..\emptyset\}$
DA	DAM	Volume required, $d_{t,1}$ Quality Reqs., $\{\mathbf{w}, \mu_{\mathbf{t,1}}, \rho_{\mathbf{t,1}}..\emptyset\}$	Volume to supply, $x_{t,1}$, Supply period, $\pi_{t,1}$
DA	LAKE	Volume required, $d_{t,2}$ Quality Reqs., $\{\mathbf{w}, \mu_{\mathbf{t,2}}, \rho_{\mathbf{t,2}}..\emptyset\}$	Volume to supply, $x_{t,2}$, Supply period, $\pi_{t,2}$
LAKE	ENERGY	Energy required, $e_{t,2}$, Supply period, $\pi_{t,2}$	Start time, $\pi^b_{t,2}$, Completion time, $\pi^e_{t,2}$, where $\pi_{t,2} = \pi^e_{t,2} - \pi^e_{t,2}$
DAM	ENERGY	Energy required, $e^r_{t,1}$, Energy produced, $e^p_{t,1}$, where $e_{t,1} = e^p_{t,1} - e^r_{t,1}$, Supply period, $\pi_{t,1}$	Start time, $\pi^b_{t,1}$, Completion time, $\pi^e_{t,1}$, where $\pi_{t,1} = \pi^e_{t,1} - \pi^e_{t,1}$
PA	ENERGY	Schedule for supply, $\Pi_t = \{\pi^i_{t,n} \mid n = 1, 2, i = b, e\}$	Confirmation

Table 1 presents the type of data and information exchanged in between the agents while interacting to agree on collective behaviour for optimum water production. Few new notations, $d_{t,n}, e^r_{t,n}, e^p_{t,n}, \Pi_t, \pi^b_{t,n}, \pi^e_{t,n}$, are introduced in the table as part of *request* and *response* messages between requesting and responding agents and described in the table. Once communication is completed, the agents on both ends will mutually confirm.

The second entry into the water resource management system, as sketched in Figure 4, comes through DAM agent as a stimulus, particularly when the water level in the DAM excesses a pre-set upper boundary. The system accepts y_t as the volume of water to be discharged from DAM as matter of urgency. Let $\lambda_{min,1}$ and $\lambda_{max,1}$ denote the thresholds for minimum and maximum water levels in the DAM. Then, $y_t = l_{t,1} - \lambda_{max,1}$, which will be stimulating the system until the water level reaches $l_{t,1} \leq \lambda_{max,1}$. The water volume of y_t is first passed to PA to evaluate if it is in sufficient quality level and needed to be considered for supply outstanding demand. If the quality level is satisfactory and there is an outstanding demand, PA will allocate this amount to corresponding water tower for processing while generating $e_{t,1}$ quantity of power, otherwise, it will be used for producing energy, $(e_{t,1})$. Obviously, the implemented MAS system for water production does not only consists of the two entry points as sketched in Figure 4, there are few communication and agreement episodes are provided in Section 4.

The multi agent model presented above is implemented considering the scenario described above with more specific data and parameters. The main focus goes on PA since it plays a very coordinating role as seen in Figure 4. Therefore, the mathematical model presented above has been further specified with parameters to fit in problem structure specified in the scenario. Few episodes of collective behaviours have also been introduced with details of agent interactions in the following sections.

3.4. Implementing planning model

This subsection provides an implementation of the mathematical model presented in Section 2.2 with data provided for a more specific case. It is supposed that there are 2 water reservoirs; one natural lake and one constructed dam. As described above, the fresh water from the natural lake is much cleaner and in better mineral structures that what is extracted from constructed dam, while the water from constructed dam can be used for power generation. There is one water tower in which extracted water volumes are further processed towards desired quality level. It can pump water to water tower if its cleanness is above a particular quality level, otherwise the water will be used for power generation only.

The model given in Eq: (11) - (15) is derived to be more specific to the circumstances described above for any time period, which can be specified as in the following subsections. It is important to note that the water quality constraint given with Eq: (14) consists of the sum of 2 fractions, where the quality parameters have been identified as weighted sum of all quality parameters. The fractions impose a non-linear (quadratic) relationship, which is required to be taken in consideration, ideally to be linearised for linear programming problem solvers. Obviously, the new model requires to be further specific with a particular time period and more parametric data, which come in the next 2 subsections.

$$
\begin{aligned}
&\textbf{Minimise} && \\
Z_p &= \sum_{t=1}^{T} c_{t,1}x_{t,1} + c_{t,2}x_{t,2} && (11)\\
&\textbf{Subject to:} && \\
x_{t,1} + x_{t,2} &\geq D_t \quad \forall t \in T && (12)\\
x_{t,n} &= \begin{cases} 0, & l_{t,n} \leq \lambda_{min,n} \\ x_{t,n}, & \text{otherwise.} \end{cases} \quad \forall n \in N \quad \forall t \in T && (13)\\
\frac{q_{t,1}}{x_{t,1}} + \frac{q_{t,2}}{x_{t,2}} &\geq \Omega \quad \forall t \in T && (14)\\
& x_{t,1} \text{ and } x_{t,2} \in \mathbb{R} && (15)
\end{aligned}
$$

4. Numerical Results and Discussions

In this section, the multi agent model developed above for planning and control of water production is demonstrated for daily supply across a typical time period of a week. As expected, the planning stage is executed to populate the planning agent (PA) with relevant knowledge and data. Then, the production will controlled through out of daily operations.

4.1. Planning for weekly demand

Planning agent, PA, requires to run the mathematical model given in Eq: (11) - (15) to plan water production for a time period of 1 week to meet related demand. Suppose that corresponding data is collected and fed into the model; then it turns the following format. The data are the cleaning / processing cost per unit volume for the first and second water sources is $c^c_{t,n} = \{2, 10\}$, the pumping cost is $c^p_{t,n} = \{15, 3\}$ and the positive cost (gain) arising from energy production is $c^q_{t,n} = \{0, 32\}$. The logic explained in Section 2.2 has been applied to these cost data and corresponding costs obtained as $c_{t,n} = \{-20, 17\}$. It is assumed that the cost components do not change over daily basis, therefore, they remain the same over the whole time period of 1 week (7 days). The daily demand is known to be as $d_t = \{150, 145, 152, 155, 148, 149, 150\}$ thousand tons, while the quality ratio is

$q_{t,n} = \{0.65, 0.35\}$, the water quality limit value is $\Omega = 120$, and the lowest water levels are $\lambda_n = \{3000, 10000\}$ thousand tons, which is worked out in a particular way and upper limits per $x_{t,n}$ calculated as $\{100, 80\}$ per day or $\{80, 100\}$. The model is revised as in the Eq: (16) – (21), which has turned into a very simplified form.

$$\begin{aligned}
&\textbf{Objective function:} && \\
Z_p &= \sum_{t=1}^{7} 17x_{t,1} - 20x_{t,2} && (16) \\
&\textbf{Subject to:} && \\
x_{t,1} + x_{t,2} &\geq d_t \quad \forall t = 1...7 && (17) \\
0.65x_{t,1} + 0.35x_{t,2} &\geq 120 \quad \forall t = 1...7 && (18) \\
x_{t,1} &\leq 100 \quad \forall t = 1...7 && (19) \\
x_{t,2} &\leq 80 \quad \forall t = 1...7 && (20) \\
& x_{t,n} \in \mathbb{R} && (21)
\end{aligned}$$

Table 2: Optimum plan for daily water production supplied from both Lake and DAM with different capacities for 7-day time period, $T = 7$

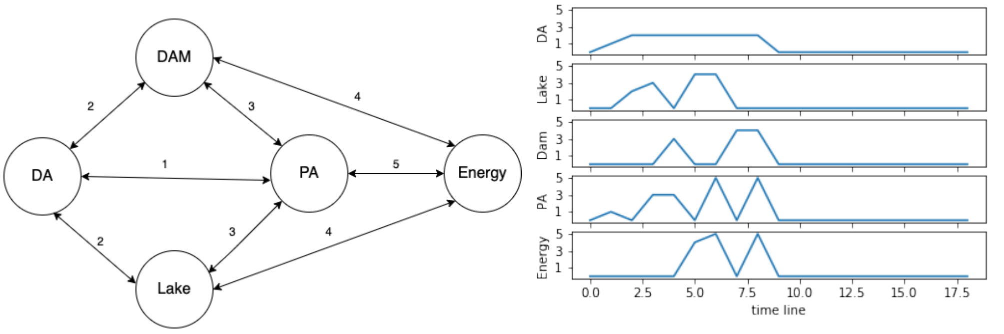
Day (t)	**Demand** (d_t)	**Lake** ($x_{t,1}$) (100 ton/day)	**DAM** ($x_{t,2}$) (80 ton/day)	**Lake** ($x_{t,1}$) (80 ton/day)	**DAM** ($x_{t,2}$) (100 ton/day)
1	150	70	80	50	100
2	145	65	80	45	100
3	152	72	80	52	100
4	155	75	80	55	100
5	148	68	80	48	100
6	149	69	80	49	100
7	150	70	80	50	100

4.2. Production control of weekly demand

The production plan developed and specified above has been solved to optimum with linear programming tools. This does not mean that the water production will exactly follow the plan without any variations subject to real circumstances of production environment. The plan will be executed through the day time until the water produced met daily demand. The following episodes are to demonstrate how MAS controls the water production process for daily demand, where each episode is a cycle of communication among the team of agents to make a decision for taking an action and tackling any emerging issue.

4.2.1. Episode 1

This episode consists of a very typical cycle of communication to initiate the daily water production in which *DA* starts interacting with PA for retrieving relevant plan and schedule, then interacts with *DAM* and *Lake* agents for their portion of supply subject to the circumstances. If the quality level declared by each remains within the limits, the production is initiated. Meanwhile, both *DAM* and *Lake* agents interact with *PA* to conform their positions with the plan to run and with *Energy* agent to update their energy consumption and production needs and information. We note that water supply from *DAM* resource contributes to power generation while supply from *Lake* requires consuming power to supply. All related data and information exchange takes place through communication episodes are detailed in Table 1.



(a) Communication order among agents

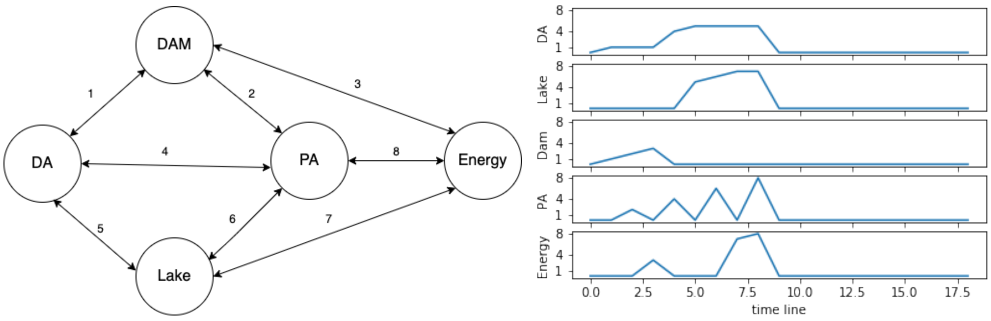
(b) Individual interactivity of agents within the episode

Figure 5: An episode of agents' interaction to initiate a daily water production

Figure 5 presents the logic of communication among multiple agents taking part of water production control, where the graph provided in Figure 5a represents the communication order within the team; the nodes present named agents and the bi-directional connectors represent the interactions in between two agents, the numbers that label the connectors is the order of communication within the team. For instance, the connector between *DA* and *PA* declares that this is the first interaction this episode of communication. On the other hand, Figure 5b is a multi-plot figure represents the engagements of individual agents through out of the episode.

4.2.2. Episode 2

This episode is about the cycle of communication activities to tackle the alerts issued due to quality and capacity problems. It is reported that on day 4 of the week, at mid-day time, *DA* is alerted of that the quality level of supplied water from *DAM* falls short - below acceptable parametric threshold of muddiness. Than, *DA* issues an alert to the rest of agent team to initiate an new episode of decision making. The next step, as appears in Figure 6a, is that *DA* contacts *DAM* to stop water supply into the tower. Then, *DAM* updates *PA* and *Energy* of the new circumstances. *DA* interacts with *PA* to re-plan and re-schedule the supply allocations.



(a) Communication order for Episode 2

(b) Agents' interaction for Episode 2

Figure 6: Episode 2: *DAM* stops supplying water due to emergency

As soon as informed, *PA* realises that each water resource has supplied the half of planned daily volume allocated to each. *PA* reconsiders the planning model, identifies restrictions imposed, and realises that the daily allocated capacity from each resource falls short to meet the daily demand. This can be observed from Eq. (19) and (20). These two constraints are revised accordingly to let meet the daily demand from *Lake* this time, borrowing some capacity reserved for security use. The new constraints are relaxed as follows: $x_{t,1} \leq 180$ is to replace Eq. (19) and $x_{t,2} = 0$ is to replace Eq. (20). The new model is solved to optimum and the obtained results are tabulated in Table 3, where water volume allocated to *DAM* is set to 0, while water supply from *Lake* is set to maximum capacity as seen. The original demand for day 4 was 155 tons – 55 tons were allocated to *Lake* and 100 tons to *DAM* to supply in the original plans as can be observed from Table 2. Approximately, half of the allocated volumes, 25 and 50 delivered by *Lake* and *DAM*, respectively, which makes up 75 tons. The rest of demand, 80 tons now all allocated to *Lake* under the new circumstances.

Table 3: New optimum plan for daily water production supplied from both *Lake* and *DAM* for the rest of 7-day time period,

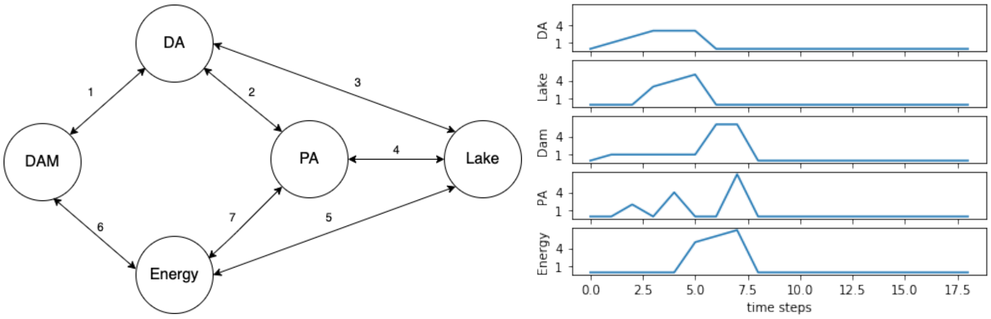
Day (t)	**Demand** (d_t)	**Lake** ($x_{t,1}$) (180 ton/day)	**DAM** ($x_{t,2}$) (0 ton/day)
4	80	80	0
5	148	148	0
6	149	149	0
7	150	150	0

Once *PA* revised the plan and the schedule, *DA* is informed, then, the new plan and supply schedule is sent to *Lake* by *PA* on its request for the rest of delivery including the relaxation to use security capacity for the given circumstances. *Lake* communicates with *Energy* to request power supply for pumping with given power consumption time period details. *Energy* confirms with *Lake* and updates *PA*. That concludes Episode 2. The individual engagement of each peer agent as part of interaction within Episode 2 is shown in Figure 6b, where *DA* remains active until the complete decision is made, while the other agents act upon arriving requests.

4.2.3. Episode 3

This episode is to reflect the communication cycle within the team of agents to decide how to let *DAM* to resume supplying to water tower for taking part of water production process. It is known that the water quality parameter of muddiness is back to level of meeting the requirement at the end of day 4. *DAM* takes initiative to inform the team of agents for re-instantiating the original restrictions and start contributing to the process. As seen in Figure 7a, *DAM* updates *DA* of the fitness to the quality, then, *DA* interacts with *PA* first to revise the plan and generate the new schedule.

PA reverts capacity constraints to the original as in Eq. (19) and (20) with a slight change to let *Lake* refill the security capacity used to cover the shortage of supply from *DAM* in the previous episode. The new constrains turn to be $x_{t,1} \leq 80$ and $x_{t,2} \leq 108$, where the original upper boundary for *DAM* is increased by 8 tons per rest of remaining days of the week to let *Lake* reserve sufficient capacity for next emergency case. As soon as *PA*



(a) Communication order within the Episode

(b) Agents' interaction across Episode 3

Figure 7: Episode 3: Communication details of agent team to let *DAM* resume supplying water

completes re-planning and generates the new schedule, *DA* is informed, the new schedule is shared with *DAM*, *Lake* and *Energy*, then, *DAM* and *Lake* updates their need for power and contribution to power. This will conclude this episode. Communication details of each peer agent as part of Episode 3 are reflected on Figure 7b, where *DAM* remains active throughout the entire episode, while the rest take part of the communication upon request. Once all confirm their role and posses up-to-date information, the episode is concluded.

Table 4: New optimum plan for daily water production supplied from both *Lake* and *DAM* with new capacities for rest of 7-day time period. This is the new supply schedule to let *DAM* resume contributing water production

Day (t)	**Demand** (d_t)	**Lake** ($x_{t,1}$) (80 ton/day)	**DAM** ($x_{t,2}$) (108 ton/day)
5	148	40	108
6	149	41	108
7	150	42	108

Water supply from both resources, *DAM* and *Lake*, throughout one week time period for water production and control using multi-agent system (MAS) described above. The progress of production control with MAS has been demonstrated through episodes presented in Figure 8, emerging issues have been tackled accordingly. The graphs present hourly water supply per resource plotting the volume of untreated water hourly supplied from both *DAM* and *Lake*, where *Lake* contributes less following the optimised plan and schedule tabulated in Table 2. It can be observed that there is fluctuation on the graph between 80 – 100 hours on horizontal axis, which reflects the supply stop applied to *DAM* due to muddiness level and resumed after 12 hours. The plots also demonstrates the change in the model due to temporary capacity extension for *DAM*.

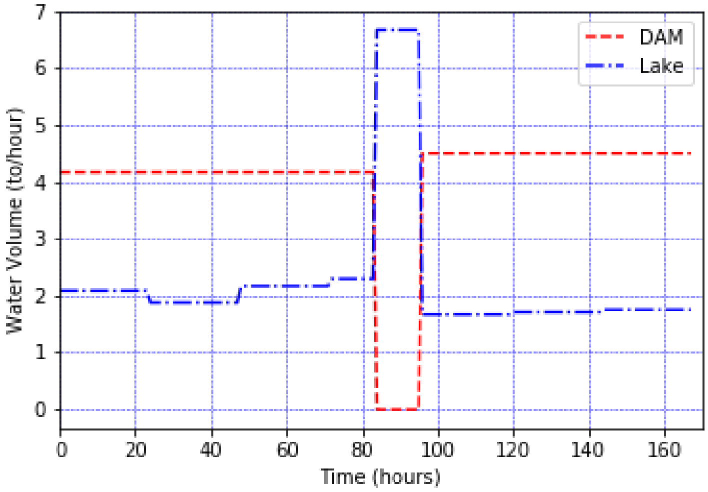


Figure 8: Untreated water supply from *DAM* and *Lake* for the complete 7-day time period

5. Conclusions

We have presented a multi-agent approach to handle water production process of water resource management for metropolitan area of a hypothetical middle-size city assuming that the water is supplied through a natural lake and a constructed dam. Water production is followed by a well-organised distribution phase, which is left out of the scope of this study. Water production is supplied with untreated water from resources and applies operations to process water to a desired quality. Due to characteristics of untreated water from each resource would be different, a decision is required to be made each time period to supply from one of the resources subject to the quality and capacity constraints. On the other hand, it is known that water supply from the constructed dam can also be used for power generation through hydro-power plant integrated into water supply facilities. This brings more complexity items in solving this planning and control problem. Water resource management, as a typical activity of enterprises, includes two fundamental stages by its nature; planning and control. In this paper, we propose solutions for each stage, which makes our proposal a framework for enterprise level water resource management. Planning stage is handled via optimisation models, which suggest optimum breakdown of supply from each resource assuring that the incurring cost, including energy consumption, remains minimum, and the power generation is conducted in its highest capacity. Once the planning is done, then the control of the real-time supply comes to the scene, which is proposed to be handled with a multi-agent-based approach.

The generic planning model for water production is implemented in Section 4 based on very hypothetical data generated for the proof-of-concept purpose, and not yet validated to suit real cases. The optimum planning results tabulated in Table 2 and the production control using a multi-agent system has been demonstrated accordingly throughout episodes. Figures 5, 6, 7, 8 and Table 3, 4 show corresponding details which demonstrate the control of water production. Episode 1 reflects how the agent team agrees to start daily production process, while Episode 2 and 3 demonstrate how the agent team takes action upon emerging circumstances to collectively develop emergent behaviour, accordingly. Energy prices are included in costings, while the amount of power generation can also be calculated once the functional relation power generation per unit of water volume is redefined, which remains as a future work.

The planning model is a single optimisation model in which a single quality measure, which is cost it this case, has been considered. Further to this study, a multi objective optimisation model can be developed converting energy functions into another objective to sit alongside cost function. This is due to that energy saving and power generation should play more active role in optimisation process rather being treated as a standard constraint. The same logic applies to water quality, which is statically considered in the model. The quality of water can also be linked to more realistic estimation, and be adopted as another objective. These are future directions of this undergoing study yet to be investigated further.

References

[1] Anonymous, Un global issues: Water, `https://www.un.org/en/sections/issues-depth/water/` (August 2019).

[2] D. Abdulbaki, M. Al-Hindi, A. Yassine, M. A. Najm, An optimization model for the allocation of water resources, Journal of Cleaner Production 164 (2017) 994–1006.

[3] D. Y. Miao, Y. P. Li, G. H. Huang, Z. F. Yang, C. H. Li, Optimization model for planning regional water resource systems under uncertainty, Journal of Water Resources Planning and Management 140 (2) (2014) 238–249.

[4] Y. Zhou, S. Guo, C. Y. Xu, D. Liu, L. Chen, D. Wang, Integrated optimal allocation model for complex adaptive system of water resources management (II): Case study, Journal of Hydrology 531 (3) (2015) 977–991.

[5] Y. Zhou, S. Guo, C. Y. Xu, D. Liu, L. Chen, Y. Ye, Integrated optimal allocation model for complex adaptive system of water resources managmenet (I): Methodologies, Journal of Hydrology 531 (3) (2015) 977–991.

[6] Z. H. Fu, H. J. Zhao, H. Wang, W. T. Lu, J. Wang, H. C. Guo, Integrated planning for regional development planning and water resources management under uncertainity: A case study of Xining, China, Journal of Hydrology 554 (2017) 623–634.

[7] L. E. H. Eda, W. Chen, Integrated water resource management in peru, Procedia Environmental Science 2 (2010) 340–348.

[8] F. Amigoni, A. Castelletti, M. Giuliani, Modeling the management of water resources systems using multi-objective (dcops), in: 2015 International Conference on Autonomous Agents and Multiagent Systems, International Foundation for Autonomous Agents and Multiagent Systems, 2015, pp. 821–829.

[9] M. E. Aydin, R. Keles, Energy efficient water resource management and optimisation: A multi agent approach, in: 10th International Symposium on Intelligent Manufacturing and Service Systems, Sakarya University, Turkey, 2019, pp. 417–426.

[10] J. Nicklow, P. Reed, D. Savic, T. Dessalegne, L. Harrell, A. Chan-Hilton, M. Karamouz, B. Minsker, A. Ostfeld, A. Singh, E. Zechman, State of

the art for genetic algorithms and beyond in water resources planning and management, Journal of Water Resources Planning and Management 136 (4) (2010) 412–432.

[11] L. Wang, L. Fang, K. W. Hipel, Basin-wide cooperative water resources allocation, European Journal of Operational Research 190 (3) (2008) 798 – 817.

[12] C. Perera, C. H. Lui, S. Jayawardena, The emerging internet of things marketplace from an industrial perspective: A survey, IEEE Transactions on Emerging Topics in Computing 3 (4) (2015) 585–598.

[13] M. P. Singh, A. K. Chopra, The internet of things and multiagent systems: Decentralized intelligence in distributed computing, in: IEEE 37th International Conference on Distributed Computing Systems (ICDCS-2017), IEEE, Atlanta, GA, 2017, pp. 1738–1747.

[14] S. Bosse, Mobile multi-agent systems for the internet-of-things and clouds using the JavaScript agent machine platform and machine learning as a service, in: IEEE 4th International Conference on Future Internet of Things and Cloud (FiCloud), IEEE, Vienna, Austria, 2016, pp. 244–253.

[15] A. Gunkel, The application of multi-agent systems for water resources research–possibilities and limits (Doctoral dissertation), PhD Thesis, Institut fur Hydrologie der Albert-Ludwigs-Universitat Freiburg, Freiburg, Germany (2005).

[16] Q. Han, G. Tan, X. Fu, Y. Mei, Z. Yang, Water resource optimal allocation based on multi-agent game theory of HanJiang river basin, Water 10 (9) (2018) 1184–1192.

[17] M. Giuliani, A. Castelletti, F. Amigoni, X. Cai, Multiagent systems and distributed constraint reasoning for regulatory mechanism design in water management, Journal of Water Resources Planning and Management 141 (4) (2015) 0401–4068.

[18] T. Archibald, S. Marshall, Review of mathematical programming applications in water resource management under uncertainty, Environmental Modeling and Assessment 23 (6) (2018) 753–777.

[19] M. E. Aydin, Coordinating metaheuristic agents with swarm intelligence, Journal of Intelligent Manufacturing 23 (4) (2012) 991–999.

[20] M. E. Aydin, Metaheuristic agent teams for job-shop scheduling problems, Lecture Notes in Computer Science 4659 (2007) 185–194.

[21] M. E. Aydin, E. Oztemel, D. Nashawati, M. Odeh, A. Mansour, An agent-based approach for strategic alignment in enterprise systems: A Cancer Care Case, in: 1st International Conference on Cancer Care Informatics (CCI-2018), IEEE, Amman, Jordan, 2018, pp. 1–7.

[22] M. Hadipour, J. F. Derakhshandeh, M. A. Shiran, An experimental setup of multi-intelligent control system (mic) of water management using the internet of things (iot), ISA Transactions (2019).