Expert Systems with Applications 41 (2014) 1262–1270

Contents lists available at ScienceDirect

Expert Systems with Applications

journal homepage: www.elsevier.com/locate/eswa

Self-adaptive obtaining water-supply reservoir operation rules: Co-evolution artificial immune system

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ARTICLE INFO

Keywords:
Water-supply reservoir
Operating rules
Complexity adaptive system
Co-evolution artificial immune system

ABSTRACT

We investigated the complexity of reservoir operation and management as a complex adaptive system in this paper. Based on similarities between the process of extracting reservoirs operating rules and the self-adaptive learning behavior of antibody to antigens in the human immune system, a novel reservoir operating rule extraction architecture is proposed. By using the established co-evolution artificial immune system model (Co-EAISM), a case study of a single water-supply reservoir to provide water consumption for municipals, industries and agricultural irrigation is also presented.

Twenty four rules are obtained eventually via Co-EAISM after 500 generations. It is demonstrated that they can identify 92.5% of the training samples and 84.4% of the testing samples, while obtaining the shortage index 2.23(10^{14} m^6) between the predicted and practical release during the testing, which are beyond those by using Radius Basis Function (RBF) as a data mining technology for extracting water-supply reservoir operating rules. Three aspects of operating rule diversity, generality and non-linear division are discussed, considering behaviors, performances and impact factors of the Co-EAISM over the evolution.

Through the modeling data and the presented case study, the proposed model has some benefits: (a) it is feasible and effective for self-adaptively extracting the reservoir operating rules to provide a novel route for reservoir operation management; (b) it can self-adaptively track the rules, adjust the population of the rules in corresponding to complex operation environment, and make reasonable release decisions; (c) it drives the rules diversity emergence to capture many niches composed of the operating samples with similar operating attributes, to achieve the non-linear division of the operating samples in the binary space, which helps to acquire the spatial distributions of samples and gain the reservoir operation experience; (d) it can also explore the binary space to deal with subsequent complex changes of the operation environment via the character "#" in the schemas of the rules, and furthermore provide sufficient decision-making information in view of the physical meanings of the gene schemas contained in the rules.

1. Introduction

The growing shortage of water resources calls for more efficient water resource management. However, a water resource system is a complex adaptive system (CAS). It comprises many agents such as reservoir, water-users, governments and ecology etc. Moreover, the water resource management is facing more challenges from economics, society and environment, and difficult to coordinate the interest appealing from these agents for the water demand (Jeffrey & Seaton, 1997; Wang & et al., 2005; Zhao, Wang, & Weng, 2002). Reservoir acts as a key project for water control, allocation and usually plays a major role in exploitation and utilization of water resources. The reservoir also confronts increasing complexity of the operation context and constantly adjusts its' release strategies to meet with the change of operation environment. Hence, as an agent in the system, the reservoir is involved with challenges including various decision variables, multiple conflicting objectives, considerable risks, and uncertainty. It co-evolves with other agents in the water resource system by ways of collaboration and competition to get optimization (Oliveira & Loucks, 1997). Therefore, varieties of optimal models have been implemented in reservoir operation (Labadie, 2004; Wurbs, 1993; Yeh, 1985). However, the optimal releases are only hinderer insights and could not be used directly for reservoir operation (Philbrick & Kitanidis, 1999).

In reality, the operation of the long-term or real-time reservoir depends on the established operating rules, and embraces rule curves and regression functions. These principles lead the reservoirs' release to be best interests of water-supply objectives according to the current reservoir level, hydrological conditions, water demands and the time of the year. In the previous study,

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http://dx.doi.org/10.1016/j.eswa.2013.08.024

the linear or multiple regression were conventionally introduced to study the operating rules from the deterministic optimal release sequence, obtained by optimal methods such as dynamic programming or linear programming (Mizyed, Loftis, & Fontane, 1992; Young, 1967). Nevertheless, they provided general operation strategies, not allowing optimized operations in response to subsequent changes of hydrological conditions. The guide curve or tables were also used to denote operating rules to provide a mechanism for reservoir release as a function of reservoir storage (Mohan & Keskar, 1991). Moreover, several new data mining techniques, such as the artificial neural networks (ANNs), fuzzy set theory and decision tree theory, are used to obtain operating rules for the real-time operation, adaptive to the complexity due to multi-objectives, uncertainties and high dimension nonlinearities (Hasebe & Nagayama, 2002; Neelakantan & Pundarikanthan, 2000; Solomatine, 2002; Bessler et al., 2003; Yin, Wang, Hu, et al., 2006; Zahraie & Hosseini, 2009). Although these techniques allow improved operation for the multi-objective, multi-variable and non-linear inherent than some other traditional methods, their extractions are yet based on simple space division and non-linear mapping, not on comprehensive building block hypothesis. These techniques could hardly perceive the individual self-adaptive behavior of operating rules in the evolution process, as well as the emergence of group behavior. Thus, the study on acquisition way and evolutionary behavior of reservoir operation rules for complex adaptive systems is necessary and will contribute to a more profound understanding of the essence of water resource management.

Human immune system (HIS) is a highly paralleled, distributed and multi-agent complex adaptive system. It goes through the antibody over the body to identify self and non-self, and resists foreign antigenic substances invasion, with abilities of decentralized control, adaptation and learning as well as memory (Dasgupta, 1998). Artificial immune system (AIS), inspired by the HIS, is receiving significant attention in water resources management in the recent years (Chu, Lin, Liu, & Sung, 2008; Sirajul Islam & Bipul Talukdar, 2012). However, it is only applied as evolutionary search technique just as genetic algorithms (GAs) to search the optimal solutions or derive the operation rules, not as a complex adaptive system. In fact, Antibodies as agents of HIS continuously evolve and adjust its structure and behavior in response to foreign antigens. Forrest, Javornik, Smith, and Perelson (1993) and Smith, Forrest, and Pereslon (1993) investigated the self-adaptive learning ability of antibodies in HIS to recognize antigens with different types of binary schemas during the process of evolution by GAs. Furthermore, Potter and De Jong (1998), Potter and De Jong (2000) made an intensive study of the evolution and collaboration among antibody species and revealed that the species would be divided automatically into many subspecies over the evolution which leads to the diversity of species to search the niches distributed in the antigen space, and establish a co-evolutionary artificial immune system (Co-EAIS).

Based on the previous study on the Co-EAIS, this paper compares antibodies response to the antigens with the reservoir operating rule extraction, and reveals that there are two aspects about HIS thoroughly suitable for obtaining the reservoir operating rules and the adaptive management of reservoir operation. One aspect lies in the interaction between operating rules and its' influencing factors or the change environment is similar to the response mechanisms between antibodies and antigens; another is that the optimal adjustment of operating rules is also similar to the adaptive adjustment of structure and behavior of antibody in the process of co-evolution (Yin et al., 2006). Based on this concept and the literature, this paper applies co-evolution of the artificial immune system to reservoir operation management, and proposes a co-evolution artificial immune system model (Co-EAISM) to derive operating rules with a case of water-supply reservoir operation in the northern China. By analyzing the performances of the model deriving operating rules from three aspects of diversity, generalization and non-division ability of operating rules, a novel and effective route for reservoir operation management is demonstrated.

2. Operating rules extraction model based on the Co-EAIS

2.1. The brief overview of co-evolutionary artificial immune system

The co-evolutionary artificial immune system, proposed by Potter and De Jong (2000), consists of various species and each species is the aggregates of many *B* lymphocytes. *B* cell is constituted by the antibody and the activation threshold and they are encoded with binary strings. In the immune response to the foreign antigen, the *B* cells distributed in serum can automatically detect the invasion of antigen, recognize and learn from the binary schemas hidden in antigen. They constantly evolve their own structures and adjust behaviors by the GA through the operators of selection, crossover and mutation, self-adaptively. Each *B* cell needs to cooperate with the optimal individuals in other species via cooperative co-evolution (illustrated in Fig. 1) to bind the foreign antigen, and eventually neutralize and eliminate the antigen. Meanwhile, the species in the system compete with each other to survive under the pressure of evolution, consequently the poor species will gradually disappear and the new species will continuously generate. In this way, the system maintains the dynamic balance of *B* lymphocyte species as well as the diversity of the species to be adaptive to the changes of antigen.

The two most significant factors for the co-evolution of *B* lymphocyte species are how to assign the credit for the species and *B*-cell individual within the species, and how to control the birth or death of each *B*-cell species in the system. The *B*-cell individual credit, generally called as fitness (illustrated in Fig. 1), is the adaptability to the antigen and the credit assignment depends on the problems to be solved; the optimal *B*-cell among the population is selected as the representative of the species, and therefore the credit of the species, known as the contribution, is determined by the fitness of the optimal *B*-cell. For instance, the optimal *B*-cell credit or fitness is obtained from the procedure as follows:

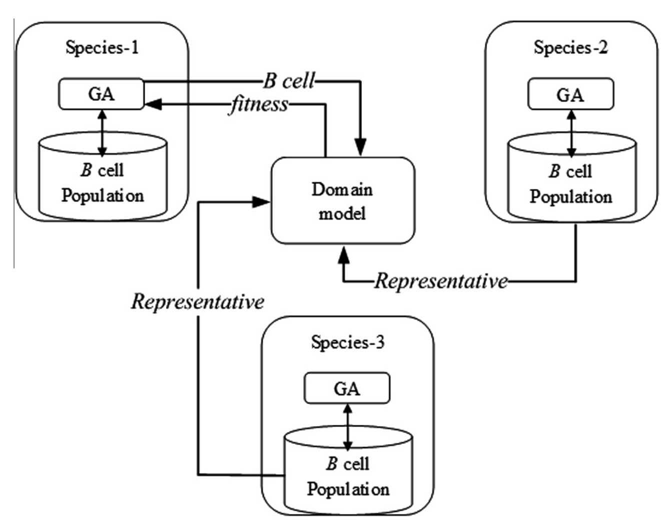

Fig. 1. *B*-cell species' cooperative co-evolution.