Computers and Chemical Engineering 104 (2017) 107–127

Contents lists available at ScienceDirect

Computers and Chemical Engineering

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

A stochastic programming approach to integrated water supply and wastewater collection network design problem

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ARTICLE INFO

Article history:
Received 23 September 2016
Received in revised form 30 March 2017
Accepted 1 April 2017
Available online 8 April 2017

Keywords:
Water supply network
Wastewater collection system
Uncertainty
Sample average approximation
Accelerated Benders decomposition algorithm
Local branching

ABSTRACT

In this paper, a mixed scenario-based and probabilistic two-stage stochastic programming model is proposed for the design of integrated water supply and wastewater collection systems. None of the existing models simultaneously takes into account both business-as-usual and hazard uncertainties. To explore suitable solutions in a reasonable time, a solving procedure comprised of the (1) sample average approximation method, (2) Bezdek fuzzy clustering method and (3) Benders decomposition algorithm is developed. In order to expedite the convergence of the applied Benders decomposition algorithm, different acceleration techniques especially the local branching method are utilized. The performance of the proposed mathematical model and solution procedure is analyzed computationally through a real case study which the results show the usefulness of the developed stochastic programming model as well as the efficiency of the solution approach.

1. Introduction

Water supply and wastewater collection system is a set of physical infrastructures designed to purify water from various relatively high-quality water supplies, then deliver it to multiple demand centers (e.g. agricultural, domestic, industrial and commercial centers) and finally collect the waste water (Chung et al., 2009; Liu et al., 2011). For designing and planning of such systems in addition to simulation-based approaches (Chung et al., 2008), operations research techniques broadly have been used since fifty years ago (Gupta, 1969). It should be noted that the integration of water supply system with wastewater collection system prevents the suboptimal designs resulted from separately considering these two systems. Due to systemic and environmental sources of uncertainty as well as strategic long-term planning horizon of water supply and wastewater collection system (WSWCS) design problems, the uncertainty is an issue typically such systems should confront with. Maier et al. (2014) corroborate that WSWCSs are hemmed in by uncertainty, and they also elucidate that if uncertainty is neglected in a WSWCS design problem, suboptimal or reckless solutions will come as consequences. Based on the frequency of occurrence and the level of disruptive impact, uncertainty can be divided into *business-as-usual* and *hazard* uncertainties (Naderi et al., 2016). *Business-as-usual* corresponds to the case where the frequency of occurrence is high and the level of disruptive impact is low. On the other hand, *hazard* is related to low frequency but high disruptive impact events. Particularly, in WSWCS problems, *business-as-usual* uncertainty includes, but not limited to, variabilities in the supply and demand of water. Based on the quality of data available for *business-as-usual* events, different methods such as probability theory, fuzzy set theory and rough set theory can be used to model such events. In the presence of epistemic uncertainty which refers to the data stated in the form of linguistic variable, fuzzy programming approaches are applied in the relevant literature. It is the case, also under conditions in which historical data is not available or costly to grasp (e.g. Faye et al., 2005; Xu and Qin, 2014; Lee and Chang, 2005; Bender and Simonovic, 2000; Jairaj and Vedula, 2000). In the cases of deep uncertainty, where it is only possible to allocate upper and lower bounds to uncertain parameters, mostly interval programming approaches have been used by researchers (e.g. Chung et al., 2009; Housh et al., 2011). Finally, in the presence of sufficient and reliable historical data, stochastic programming approaches are employed to handle uncertainty (e.g. Kapelan et al., 2005; Babayan et al., 2005; Kang and Lansey, 2012; Housh et al., 2013; Pallattino et al., 2005; Escudero, 2000; Huang and Loucks, 2000). Meanwhile, in the cases where various types of data constitute

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http://dx.doi.org/10.1016/j.compchemeng.2017.04.003
0098-1354/

a hybrid uncertain environment, approaches like fuzzy stochastic programming (see Wang and Huang, 2011; Li et al., 2009; Maqsood et al., 2005) and interval stochastic programming (see Luo et al., 2003; Li et al., 2006; Li and Huang, 2007) turn out to be appropriate. However, in most of real cases, the reliable historical data conveniently can be obtained from water-related organizations. Thus, attributing empirical probabilistic distributions to uncertain parameters won't be an onerous task. Accordingly, stochastic programming approaches seem to be beneficial in many cases and the body of literature attests to this fact.

In the cases where continuous/empirical distributions are attributed to the random parameters, a key complication concerning the evaluation of objective function might arise, because an expectation value will appear in it, and the exact evaluation of the expectation requires to solve a complicated multiple integral which is impossible in many cases (Santoso et al., 2005). To circumvent this difficulty, the sample average approximation (SAA) method developed by Kleywegt et al. (2002) can be applied. The SAA technique is a solution approach aiming to approximate the expectation in the objective function of two-stage stochastic programming problems. In this method, in each iteration, firstly a number of random samples for uncertain parameters are generated and then based on these samples, an equivalent crisp model called the sample average approximating problem is developed. The resulting sample average approximating problem is solved by one of the deterministic optimization techniques. The process is repeated with different samples until statistical estimates of optimality gaps reach their desirable values. If we want to attribute continuous/empirical distributions to the random parameters of a WSWCS design problem, inevitably, an expectation value will appear in the objective function, and thus we must plan a scheme for calculating it. In most of WSWCS design problems existing in the literature, simply random parameters are substituted with their mean values while it is obvious that this plan only obtains a rough estimation of the expectation value and simply neglects the deviation of uncertain parameters. Despite the fact that in the field of stochastic programming, the SAA has been successfully examined against the mean value strategy, no work in the WSWCS design problem literature takes advantages of the mentioned method.

As previously discussed, hazards are low frequency but high disruptive impact uncertain events. Catastrophes and natural disasters, most notably earthquakes, floods and droughts, are the perfect instances of hazards in WSWCS which can cause significant losses and malfunction of facilities (Grigg, 2003). For example, in Japan, the Kobe's earthquake of 1995 had been the reason of $100 billion damage to the WSWCS (Chung et al., 1996). The Midwestern United States flood of 1993 had incurred about $15 billion losses (Horsley et al., 1994). Extreme droughts in the United States had caused $144 billion damage between 1980 and 2003 (Dai et al., 2004). Other types of hazard in WSWCS are associated with human-related threats. These types of hazard have received little attention but threaten WSWCS components as well. Sabotage, employee strike and terrorist attack are some of the salient instances of human-related hazard disturbing usual performances of WSWCSs. Hazard can be embedded in WSWCS design mathematical models with the aid of scenario generation on the basis of each type of hazard. However, the computational encumbrance might significantly arise, if we consider each type of hazard separately. This difficulty can be circumvented by either of multi-hazards, i.e. aggregate extreme events (see Gogu et al., 2005; Scawthorn et al., 2006) or scenario reduction methods. In the water resource management context, a considerable body of literature is devoted to identifying potential hazards, and assessing corresponding risks on WSWCSs (e.g. Salas et al., 2005; Shiau and Shen, 2001; Lund, 2002; Eisenberg et al., 2001; Seica and Packer, 2004; Ostfeld, 2001). Nevertheless, to the best of our knowledge, no work can be found in the relevant literature considering different types of hazards in WSWCS design decisions. However, most recently, Lan et al. (2015) have formulated operational failures of facilities within a mathematical optimization model. Also, Mortazavi-Naeini et al. (2015) have proposed a mathematical model taking into account the natural climate cycles. Adverse consequences of neglecting uncertainty which is enumerated by researchers, necessitate comprehensive study and modeling of all varieties of uncertainty in WSWCSs.

WSWCS design problems typically include decisions about the establishment of water and wastewater treatment centers, the installation of pipelines, the construction of pump stations, the establishment of tanks, and the determination of capacities. All of the aforementioned decisions can be modeled as integer decision variables. In addition, it is incumbent upon these problems to determine the recharges between facilities by modeling them as continuous decision variables. Therefore, most of WSWCS design mathematical models are in types of mixed-integer programming models. The Benders decomposition (Benders, 1962) is a resolution strategy which has been deployed appropriately in the field of complex mixed-integer programming problems like shift scheduling problems (e.g. Rekik et al., 2008), scheduling problems (e.g. Chu and You, 2013), supply chain network design problems (e.g. Pishvaee et al., 2014) and network planning problems (e.g. Lee, 2013). In the Benders decomposition algorithm, the original complex mixed-integer programming problem is decomposed into a simple mixed integer programming (master problem) problem and a pure continuous linear programming problem (sub-problem). These two problems are solved iteratively by using the solution of one in the other, until solutions of the master problem and the sub-problem are converged. The classical Benders algorithm has been also applied in a WSWCS design problem recently by Lan et al. (2015). But the direct application of the classical Benders decomposition algorithm does not necessarily lead to a fast convergence (Saharidis and Ierapetritou, 2010; Yang and Lee, 2012). In these cases, the application of different acceleration methods profoundly influences the efficiency of the algorithm.

Modeling a WSWCS design problem considering business-as-usual and hazard uncertainties, as well as integrating the water supply system with the wastewater collection system, leaded to a complex mixed integer scenario-based problem with an expected value appearing in the objective function. Thus, it is needed to develop a methodology which could at first handle a huge number of scenarios, at second include an efficient method for calculating this expectation value and above all, obtain solutions in a reasonable time. These are our motivations to integrate the Bezdek fuzzy clustering method, SAA, and accelerated Benders decomposition. The first one is used for handling scenarios, the second for dealing with the expectation value and the last for gaining solutions of a complex mixed integer problem in a reasonable time. Different acceleration techniques, especially the local branching method significantly has enriched the convergence characteristic of the proposed Benders decomposition algorithm. Implementing and comparing this broad range of acceleration techniques is one of the unique characteristics of the paper which helps researchers to know when, where and which acceleration techniques should be used. The applicability of the proposed approach not to be retained in the water resources management scope but could be broadened to every network design problem.

The rest of this paper is organized as follows. Section 2 describes the concerned WSWCS problem and thereafter, the concerned mathematical formulation is presented in Section 3. The proposed hybrid solution strategy is elaborated in Section 4. The performance of the proposed stochastic programming model as well as the solution approach is investigated in Section 5 through a real case study. Finally, Section 6 concludes the paper and presents some future research directions.