Resources, Conservation and Recycling 108 (2016) 21–40

Contents lists available at ScienceDirect

Resources, Conservation and Recycling

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

Sustainable urban water resources management considering life-cycle environmental impacts of water utilization under uncertainty

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ARTICLE INFO

Article history:
Received 7 October 2015
Received in revised form 9 January 2016
Accepted 11 January 2016
Available online 21 January 2016

Keywords:
Water resources management
Fuzzy sets
Two-stage programming
Life cycle analysis

ABSTRACT

To improve applicability of life cycle assessment (LCA) in supporting direct and robust decision-making, an integrated approach was developed through incorporating operational research and uncertainty analysis methods within a general LCA framework. The methodology can (a) help comprehensive evaluation of environmental impacts at multiple product-service levels, (b) facilitate the reflections of multiple LCA associated uncertainties and transfer them into consequential decision-making process, and (c) identify desired water allocation schemes for minimizing life-cycle environmental impacts. This represented an improvement upon conventional LCA method, as well as water resources allocation. The developed method was then verified in a water-stressed city (i.e., the City of Dalian), northeastern China. The application indicated that the proposed method was effective in generating desired water supply schemes under uncertainties, reflecting the associated life-cycle environmental impacts, and strengthening capabilities of both LCA and operational research methods. The results also indicated that the top three contributors for life-cycle environmental impacts would be districts of Pulandian and Zhuanghe, and Municipal zone of the city.

1. Introduction

Freshwater is fundamental for maintaining environmental sustainability of human communities. Recently, water demand by municipal, industrial, and agricultural users is continuously increasing across the world due to economic expansion and population explosion. Thus, it is a challenging issue within a water allocation system (WAS) to effectively utilize water resources for satisfying multiple targets without causing too much environmental stress for natural water bodies and the related ecosystems (Ni et al., 2014; Zhang et al., 2014b). Potential conflicts can then arise from increasing demand for limited water resources (Zhang et al., 2014b). Particularly, in many cities across the world, high reliance on freshwater and rapid population growth has resulted in severe water tension in urban water allocation systems (UWAS) (Mankad, 2012). However, many processes and factors need to be comprehensively considered within a UWAS, such as water supply options, water source protection measures, infrastructure capital and operational costs as well as interactions within water-energy nexus systems (Loubet et al., 2014; Xu et al., 2012). The systems which consume intensive energy constantly cause many environmental impacts (Behzadian and Kapelan, 2015). These processes and factors are simultaneously fraught with a variety of uncertainties (e.g., uncertain impacts of water withdraw upon the environment, vague judgments of managers upon water price, and the stochastic distribution of precipitation that is closely related to water availability). This leads to multi-level complexities for relevant decision-making and is posing a major challenge to decision makers. Effective methods are thus desired for helping facilitate impact assessment and decision making of water related activities within UWAS (Le Bars and Le Grusse, 2008).

Conventionally, many system analysis methods were developed for supporting urban water resources management, such as life cycle analysis (LCA), operational research, and system dynamics (SD) modeling. Among them, LCA was widely used to evaluate water footprints (Gu et al., 2014; Zhang et al., 2014a) and the corresponding environmental performances for many water-related activities, such as water extraction, conveyance, and consumption (Mery et al., 2013; Zhang and Anadon, 2013; Zhang et al., 2014a).

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http://dx.doi.org/10.1016/j.resconrec.2016.01.008
0921-3449/

According to ISO (2006), LCA can be used for systematic evaluation of two or more products and processes/services in terms of their economic and environmental implications. A number of researchers assessed environmental performances of multiple water-related activities based on the method of life-cycle analysis (Del Borghi et al., 2013; Sebastian et al., 2011; Stokes and Horvath, 2009). For example, Lim and Park (2007) analyzed environmental impacts and economic costs of a water network system through life-cycle assessment. Zhang and Anadon (2013) evaluated environmental impacts of water extraction and consumption, and wastewater discharge in the energy sector of China through a hybrid input–output model and multiple LCA tools. Hendrickson and Horvath (2014) analyzed emissions and reductions of greenhouse gases (GHG) in current and future water distribution systems for California and Texas, United States. Considering environmental management in compound social-economic-engineering systems (Chung and Lee, 2009), the scope of LCA was broadened from an individual product to multiple products/services. For example, Joore and Brezet (2015) developed a LCA-based multilevel design model to analyze social and product technologies and services, within an urban social system. Guinée et al. (2010) proposed life cycle sustainability analysis, which can be performed efficiently at both product- and economy-wide levels. However, there is a challenge that makes LCA ineffective in some studies. At the stage of post-LCA, the evaluation results of environmental impacts cannot be directly used for tackling the practical problem of water-resource management and environmental-impact control.

To solve the problem of managing water systems and minimizing the associated environmental impacts from a life-cycle perspective, optimization models need to be integrated into an LCA framework. Previously, quantification of life-cycle environmental impacts was incorporated into many optimization models. For instance, Bonnin et al. (2015) established an effective management system for copper scrap recycling through hybrid LCA and multi-objective optimization approaches. Jing et al. (2012) developed a multi-objective optimization model for reflecting life-cycle environmental impacts for a cooling, heating and power generation system within a building. Gebreslassie et al. (2012) proposed a bi-objective non-linear optimization model with the consideration of life-cycle global warming potential for the cooling sector. Vadenbo et al. (2014a,b) introduced a unified framework for waste and resources management in industrial systems through combining multi-objective programming model with life cycle assessment approaches. Specifically, most of the related research considered economic performance as the objective function and did not comprehensively address environmental impacts of relevant products and services within a UWAS (Wang et al., 2013). However, few studies on optimization management were conducted from a life-cycle perspective and could address uncertainties in a UWAS (e.g., water availabilities under multiple precipitation probability levels, and water demand under varying conditions) (van Zelm and Huijbregts, 2013; Wiedmann et al., 2011). For example, Sigel et al. (2010) proposed a conceptual framework for perceiving and tackling uncertainties within the processes of environmental and water-related decision-making. Carmona et al. (2013) developed a methodological framework to support water resources management under uncertain conditions. Some researchers adopted two-stage stochastic programming (TSP) to support decision making considering occurrences of random events with multiple water availabilities (Lv et al., 2013). Moreover, subjective judgments in life-cycle analysis for imprecise or missing data may cause uncertainties that would transfer into consequential optimization models (Arena and Di Gregorio, 2014). Meanwhile, uncertainties of water resources management (e.g., the manager's vague judgments, and water availabilities under multiple probability levels) would also multiply complexities of relevant decision-making process. Traditionally, these uncertainties were quantified by a series of methods. For example, uncertainties caused by imprecise LCI data can be analyzed by Monte Carlo simulation (Leinonen et al., 2013). Variations of water availabilities can be described into probability distributions or fuzzy sets (Wang et al., 2015). Water demands in future could be estimated by interval numbers with unknown distributions (Cai et al., 2011a). Such uncertainties associated with life-cycle analysis and water resources management have been rarely considered by the previous LCA- and optimization- related studies.

Therefore, to improve the applicability of post-LCA for robust decision-making support for UWAS, systematic evaluation tools, optimization modeling, and uncertainty analysis approaches need to be incorporated within a general LCA framework. The objective of this research is to develop an integrated approach for supporting comprehensive decision-making in UWAS through the incorporation of operational research and uncertainty analysis within a general LCA framework. This method will improve capabilities of conventional LCA in terms of their applicability and uncertainty reflection. It can effectively connect life-cycle sustainability assessment with robust decision making and then be used for supporting sustainable urban water resources management, strengthening the capability of post-LCA in generating comprehensive decision alternatives under uncertainties. The methodology can (a) systematically reflect and address complexities of UWAS, and facilitate the comprehensive evaluation of environmental impacts at multiple product service levels, (b) facilitate reflections of multiple uncertainties and incorporate them into a general LCA framework, and (c) identify water allocation and manage robust action for environment-oriented water supply system design. The developed method will then be verified in a water-stressed city (i.e., the City of Dalian) in northeastern China. In detail, the objective entails the following tasks: (i) employment of multi-level life cycle analyses to systematically evaluate environmental impacts of products/services within a UWAS, (ii) adoption of an inexact optimization approach to strengthen applicability of LCA in generating water management options under uncertainties resulting from LCA results and management parameters, and (iii) application of the proposed model in Dalian, China, for demonstrating the applicability of the methodology. In this research, a fuzzy inexact two-stage programming (FITSP) model will be developed and combined with uncertainty and life cycle analysis of urban water systems for supporting decision-making in water resources management. In detail, the paper is organized as follows: (a) explanations of LCA-based decision-making under uncertain conditions will be covered in part 2, (b) specific methods (e.g., uncertainty and life cycle analysis, optimization model, and solution method) that are to be adopted in this research will be described in part 3, and (c) a studying case in Dalian City will be presented in part 4 to demonstrate effectiveness of the proposed methodology. At last, background data for life cycle analysis and case study will be listed in Appendix.

2. A systematic perspective of LCA-based decision-making under uncertainty

For conventional LCA methods, the generated results merely represent environmental impacts of relevant products and/or services in a quantitative way. They can be used for research and development (R&D) to guide emerging technologies in advance toward decreased environmental burden, providing environmental guidance for consideration alongside technical and economic measures of technology readiness (Wender et al., 2014). In terms of mature technologies, these methods can be adopted for reflect and compare environmental effects of varying products and services. In this capacity, LCA could proactively identify environmental