Inexact Optimization Theory for Resources and Environmental Management

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1. Overview of the Field

Natural resources conservation and environmental protection have been challenging many researchers and managers. Such challenges are being complicated with rapid socio-economic development associated with increasing contaminant emissions and decreasing resources availabilities (Maqsood and Huang, 2003). Moreover, resources and environmental management systems involve many interconnected components related to technical, social, environmental, institutional, political and financial aspects (Zarghaami, 2006). Such interconnections bring more system complexities than those derived from individual parts. Effective management under such complexities should be based on a variety of decision support studies. Generally, optimization models are useful tools for such a purpose. However, optimization modeling of resources and environmental systems within an interactive, dynamic and uncertain context has been beyond the conventional optimization methods (Li et al., 2006). Thus, advanced inexact optimization methodologies are desired.

Specifically, application of the optimization techniques to resources and environmental management is affected by many factors. First, the resources and environmental management systems are complicated, where a number of factors and interrelationships are hard to be expressed as mathematical formulas; also, nonlinearity that exists in system can hardly be effectively reflected. Second, information for a number of system parameters is often unavailable, such that rough estimations have to be made. Also, a large portion of information that is available may not be quantifiable; instead, this type of information could be simply the implicit knowledge from decision-makers. Inputs for an optimization model may only be a small part of the general information in a study system. Therefore, outputs from an optimization model may only be useful for providing part of decision support, while another part should be from solid investigations and analyses of the ambiguous and unquantifiable information. Third, for information that is quantifiable, a significant part of it may not exist as deterministic data. This creates difficulties in expression of the uncertainties, as well as solution for models that contain uncertain parameters and/or relationships (Kindler, 1992; Lee and Wen, 1997; Sasikumar et al., 1999).

2. Recent Developments and Open Problems

In the past decades, many inexact optimization methods were developed for supporting resources and environmental management under uncertainty (Huang et al., 1992, 1995; Maqsood et al., 2005; Li and Huang, 2006). They included approaches of stochastic mathematical programming (SMP), interval linear programming (ILP), and fuzzy mathematical programming (FMP). FMP could deal with ambiguity and vagueness in resource availabilities by representing the uncertainties as fuzzy sets; this method, however, was incapable of addressing the risk of violating uncertain constraints. SMP could reflect probability distributions in the right-hand sides of the constraints but could not handle independent uncertainties of the left-hand-side coefficients in the constraints or objective function. ILP could handle uncertainties expressed as intervals with known lower and upper bounds in the objective function and left- and right-hand sides of constraints; this method, however, had difficulties when parameters in the right-hand side had wide intervals, since highly uncertain solutions might thus be generated, leading to limited practical usefulness for decision makers.

Moreover, in the resources and environmental management systems, many system parameters are highly uncertain and their interrelationships can be extremely complicated. They can hardly be expressed as a single type of uncertainty. Meanwhile, the uncertain and contractive relationships of many factors (e.g. social preferences, economic demands, and environmental conservations) also need to be analyzed. The above complexities can become further compounded through not only interactions among the uncertain parameters, but also combinations of these uncertainties as presented in multiple formats.

Generally, most of the previous optimization methods only reflected limited aspects of multiple uncertainties associated with various system parameters and their relations. This restricted their applications to real-world problems of resources and environmental management. To facilitate robust management for resources and environmental systems, advanced optimization methodologies that are able to reflect these multiple uncertainties are recently developed. For example, Nie et al. (2007) proposed a hybrid interval-parameter fuzzy robust programming approach for waste management planning under uncertainty. Cai et al. (2007) presented a mixed interval parameter fuzzy-stochastic robust programming approach for municipal solid waste management under uncertainty. Li et al. (2007) gave a mixed interval-fuzzy two-stage integer programming and application to flood-diversion planning. Liu et al. (2009) proposed a dual interval parameter programming for municipal solid waste management under uncertainty. Guo and Huang (2008) developed a two-stage fuzzy chance-constrained programming and application to water resources management under dual uncertainties. In addition to dual uncertainties expressed as intervals and fuzzy sets, probability distributions and fuzzy sets, and dual intervals, other types of multiple uncertainties may also exist, such as the integration of intervals, fuzzy sets and probability distributions. An inexact-fuzzy-random (IFR) parameter was defined to address multiple uncertainties (Guo et al., 2010).

Therefore, this workshop aimed to introduce recent advances in integrated inexact optimization methodologies for addressing various forms of uncertainties associated with resources and environmental management systems. A number of compound approaches which have improved upon the conventional inexact optimization approaches with advantages in terms of uncertainty reflection, policy analysis and dynamic analysis were investigated and their potential application to various cases were also be discussed.

3. Presentation Highlights

Here are some highlights of the presentations made in this 2-day workshop:

(1) Dr. Gordon Huang from University of Regina presented a new method entitled factorial vertex fuzzy stochastic programming (FVFS). This method was developed by incorporating techniques of two-stage stochastic programming, fuzzy set theory, vertex analysis, and the concept of multi-level factorial designs within a general optimization framework. FVFS was capable of tackling probabilistic and fuzzy uncertainties, and of revealing interdependences of fuzzy uncertainties as well as their resulting effects on system performance. A new concept of multi-level factorial designs was proposed to take into account various combinations of α-cut levels for tackling fuzzy sets, improving upon the conventional fuzzy vertex method by enhancing the flexibility and applicability in the decision-making process. Multi-level factorial design was a powerful statistical technique to

study the effects of several independent variables (factors) with multiple levels on a dependent variable (response). For example, in a 3^k system of factorial designs which consist of k factors with each at three levels, there are 3^k treatment combinations with $3^k–1$ degrees of freedom between them. If there are n replicates, there will be $n3^k - 1$ total degrees of freedom and 3^k $(n - 1)$ degrees of freedom for error. These treatment combinations allow sums of squares to be computed for k main effects with each having two degrees of freedom; two-factor interactions with each having four degrees of freedom; … ; and one k-factor interaction with 2^k degrees of freedom. Such an approach is effective in tackling fuzzy sets and in revealing the latent interactions among fuzzy sets as well as their effects on the model response. The resulting solutions would help decision makers realize the valuable information hidden beneath the interrelationships of factors of interest and identify sound management strategies under fuzzy and random uncertainties.

(2) Dr. Xi Chen from Hohai University, China, presented an interesting approach entitled correlated-random-parameter inexact factorial programming. A group of correlated-random-parameter inexact factorial programming methods was proposed for environmental management problems under interactive random uncertainties and other complexities. Firstly, an interval linear programming (CRPFP) model where the lower and upper boundaries of interval coefficients (abbreviated as $b^-(\omega)$ and $b^+(\omega)$) are correlated random variables will be developed. The technique of factorial analysis will be introduced to evaluate the interactions between $b^-(\omega)$ and $b^+(\omega)$. The joint probability density distribution function of $b^-(\omega)$ and $b^+(\omega)$ as well as a pair of marginal distributions will be generated. An equivalent linear programming model will be built for obtaining optimal ranges of decision variables of CRPFP models given an allowable constraint-violation probability p_i, the cumulative probability distribution function (CDF) of $b^-(\omega)$ and the conditional CDF of $b^+(\omega)$ (i.e., $F_{s|t=b\text{-}(pi)}(s) = \int f_{s|t=b\text{-}(pi)}(s)ds$). Furthermore, the possibilistic features of environmental management systems, e.g., subjectivities of decision makers, will be reflected as fuzzy sets and be combined into the CRPFP model, leading to the development of a correlated-random-parameter fuzzy factorial programming (CRPFFP) model. The conventional fuzzy robust programming method will be introduced to resolve possibilistic parameters in CRPFFP models through converting them to intervals. As a result, CRPFFP models would be reduced to CRPFP models, and the optimal decision alternatives would be obtained based on the proposed CRPFP solution method. The other system complexities such as dually uncertain parameters in environmental management systems would be handled through the combination of corresponding inexact programming techniques and the CRPFP approach.

(3) Dr. Yongping Li from North China Electrical Power University, China, made a presentation to develop a factorial fuzzy-stochastic reliability-resilience-vulnerability analysis (FFRA) method by incorporating the concept of factorial designs, fuzzy stochastic variables, and reliability-resilience-vulnerability (R-R-V) measures within a general framework. FFRA was capable not only of conducting a comprehensive system assessment in the context of human and ecosystem health, but also of revealing potential interactions among system parameters expressed as fuzzy sets and probability distributions in the R-R-V computations as well as their impacts on R-R-V values. Reliability was defined as the probability of the system to be in a non-failed state $Rel = P\{S(t) \in NF\}$, where $S(t)$ is the state of the system at some time t, and NF denotes a non-failed state. Resilience is defined as the probability of a system to recover from a failed state $Res = P\{S(t + 1) \in NF | S(t) \in F\}$. Vulnerability is a quantification of the severity of the damage incurred during a system failure event $Vul = \Sigma_{j \in F}\, e(j)\, h(j)$, where $h(j)$ is the most damage that can be incurred during the jth failure instance and $e(j)$ is the probability that $h(j)$ is indeed the most damage that could have been incurred. The proposed approach would be useful for conducting a thorough R-R-V analysis under parameter uncertainties and their interactions.

4. Scientific Progress Made

This workshop made the scientific progress as follows:

(1) We applied the newly developed methodologies to real-world cases of resources and environmental system optimization. Through analyzing a number of multidimensional factors and the relevant interactions, desired optimal management strategies were generated with improved efficiencies and cost-effectiveness.

(2) We created new and/or enhance existing inexact optimization methods for resources management and environmental protection through research on newly emerging problems.

(3) We developed a set of methodologies and technologies dedicated to optimizing the resources and environmental management system in Canada.

(4)We developed expertise for graduate students and technicians in application of the developed inexact optimization approaches to solving problems of resources and environmental management. The student participants will then be capable of addressing the future challenges for governments and industries.

(5) We participated in integrated and interdisciplinary collaboration in areas that are fundamental for the design and implementation of sustainable resources and environmental management plans. This workshop not only improved the technical capacities of the participants, but also provided opportunities for different groups of participants to communicate their research outcomes. Specific workshop materials were offered, which could also be conveniently incorporated within the existing educational programs of academic institutions.

(6) We disseminated newly developed knowledge and research results to academic institutions and decision-makers, and expanded the capacities of researcher groups in the area of resources and environmental management through research of inexact optimization methods. As a consequence, the participant researchers can filter their knowledge to real-world applications in an effort to promote sustainable resources and environmental protection strategies.

5. Outcome of the Meeting

The outcome of this proposed workshop can be summarized as follows:

(i) This workshop enhanced the institution's ongoing effort for developing innovative mathematical methods for resources and environmental management systems by providing opportunities for collaboration with research partners and revealing challenges for balancing economic development and environmental management.

(ii) This workshop was explicitly built upon the development achievement of the previous or ongoing attempts at international, national and regional levels. This workshop not only deepened the existing partnerships and broadened them to new institutions as well as new faculties and departments within the partner institutions through continuous academic and education exchanges, but also advanced women’s equal participation with men as decision-makers in resources and environmental management.

(iii) This workshop was undertaken by an interdisciplinary team. The institutions' multidisciplinary expertise in effective resources and environmental management will be enhanced internationally through this workshop. The workshop also disseminated information regarding opportunities and challenges of international development to Canadian scholars and graduate students.

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