Information Sciences 346–347 (2016) 463–487

Contents lists available at ScienceDirect

Information Sciences

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

Multilevel decision-making: A survey

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ARTICLE INFO

Article history:
Received 15 August 2015
Revised 10 December 2015
Accepted 28 January 2016
Available online 10 February 2016

Keywords:
Multilevel decision-making
Bi-level programming
Fuzzy decision-making

ABSTRACT

Multilevel decision-making techniques aim to deal with decentralized management problems that feature interactive decision entities distributed throughout a multiple level hierarchy. Significant efforts have been devoted to understanding the fundamental concepts and developing diverse solution algorithms associated with multilevel decision-making by researchers in areas of both mathematics/computer science and business areas. Researchers have emphasized the importance of developing a range of multilevel decision-making techniques to handle a wide variety of management and optimization problems in real-world applications, and have successfully gained experience in this area. It is thus vital that a high quality, instructive review of current trends should be conducted, not only of the theoretical research results but also the practical developments in multilevel decision-making in business. This paper systematically reviews up-to-date multilevel decision-making techniques and clusters related technique developments into four main categories: bi-level decision-making (including multi-objective and multi-follower situations), tri-level decision-making, fuzzy multilevel decision-making, and the applications of these techniques in different domains. By providing state-of-the-art knowledge, this survey will directly support researchers and practical professionals in their understanding of developments in theoretical research results and applications in relation to multilevel decision-making techniques.

1. Introduction

Multilevel decision-making techniques, motivated by Stackelberg game theory [148] and presented by multilevel mathematical programming, have been developed to address compromises between the interactive decision entities that are distributed throughout a hierarchical organization. In a multilevel decision-making process, decision entities at the upper level and the lower level are respectively termed the *leader* and the *follower*, and make their individual decisions in sequence with the aim of optimizing their respective objectives. This decision-making process means that the leader has priority in making its own decision and the follower reacts after and in full knowledge of the leader's decision; however, the leader's decision is implicitly affected by the follower's reaction. Since this category of hierarchical decision-making often appears in many decentralized management problems in the real world, multilevel decision-making has motivated a number of researches on decision models [101,103], solution approaches [127] and applications [89].

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http://dx.doi.org/10.1016/j.ins.2016.01.084
0020-0255/

The original appearance of multilevel decision-making can be traced back to 1973, in a paper authored by Bracken and McGill [25], although a wide range of related research has been undertaken since the 1980s under the following designations: multilevel programming, multilevel optimization and multilevel decision-making. Early efforts in multilevel decision-making were primarily devoted to addressing optimality conditions and solution algorithms for solving basic linear, nonlinear and discrete problems, in which only one decision entity is involved at each decision level with the aim of optimizing a unique objective. Although the multilevel decision-making problem has been proved to be NP-hard by Ben-Aved and Blair [21] and Bard [16], many methods/algorithms have been developed for solving typical cases in bi-level decision-making problems, such as extreme point algorithms, branch-and-bound algorithms, complementary pivot algorithms, descent methods and penalty function methods [17,45]. These methods/algorithms can be considered to be traditional solution approaches for solving multilevel (mainly bi-level) decision-making problems.

From a practical point of view, there are two fundamental issues in supporting a multilevel decision-making process: one is how to develop a multilevel decision model to describe a hierarchical decision-making process, and the other is how to find an optimal solution to the resulting decision model. For the first issue, bi-level decision-making models with multiple optima, involving multiple objectives, multiple leaders and multiple followers, have been proposed to handle different characteristics at different decision levels. Tri-level decision-making, another typical multilevel decision form that is more complex than bi-level decision-making, has been well studied in model establishment. For the second issue, a set of solution approaches has been developed to solve these models. In the meanwhile, attention has been paid to uncertain issues in both model parameter determination and solution process, and fuzzy set technique has been used in both multilevel decision modeling and solution approaches.

Multilevel decision problems have recently increasingly appeared in decentralized management situations in the real world and have become highly complicated and large-scale, particularly with the development of economic integration and in the current age of big data; for example, business firms nowadays usually work in a decentralized manner in a complex commercial network comprised of suppliers, manufacturers, sales and logistics companies, customers and other specialized service functions [75,115]. Therefore, to help researchers understand the development experience of multilevel decision-making techniques and to assist practitioners to handle related decision-making problems in practice, this paper reviews the latest research on multilevel decision-making involving theoretical research results and applications, which are clustered into four categories: bi-level decision-making, tri-level decision-making, fuzzy multilevel decision-making, and applications of multilevel decision-making techniques.

Several survey papers [22,39,40,89,127,155] on multilevel programming/decision-making have been published in the last 20 years. However, these papers focus on early research on basic bi-level decision-making, either with traditional solution approaches only or a specific domain of applications. For example, the survey papers by Ben-Ayed [22], Vicente and Calamai [155] and Colson et al. [39,40] presented overviews of bi-level programming, which only focused on traditional solution concepts and approaches for solving basic bi-level decision problems. Sakawa and Nishizaki [127] reviewed interactive fuzzy programming approaches for solving bi-level and multilevel decision problems. Kalashnikov et al. [89] surveyed bi-level decision-making techniques on a specific application domain of energy networks. Although these survey papers have provided good references for researchers, there is an urgent need for an updated and more comprehensive review of recent developments in multilevel decision-making techniques. More importantly, in contrast to these papers that are limited to solution approaches for solving bi-level mathematical programming, this survey focuses on a variety of decision models, solution approaches and application domains from the perspective of different categories of multilevel decision-making.

To conduct this literature review, three main types of article are carefully reviewed: Type 1—articles on bi-level programming/decision-making; Type 2—articles on tri-level programming/decision-making and fuzzy multilevel programming/decision-making; and Type 3—articles on multilevel decision-making applications. The search and selection of these articles were performed according to the following five steps:

Step 1. Publication database identification and determination. Publication databases, such as Science Direct, ACM Digital Library, IEEE Xplore and SpringerLink, were selected to provide a comprehensive bibliography of papers on multilevel decision-making.

Step 2. Preliminary screening of articles. The search was first performed based on related keywords of multilevel decision-making. The articles were then selected as references if they satisfied one of the following criteria that they (1) proposed decision models related to multilevel decision-making; (2) developed solution concepts and approaches for solving multilevel decision problems; (3) provided a real-world multilevel decision-making application.

Step 3. Result filtering for Type 1 articles. Based on the keywords related to bi-level decision-making, these papers were divided into three groups using "topic clustering": (a) basic bi-level decision-making involving linear, nonlinear and discrete problems; (b) bi-level multi-objective decision-making; and (c) bi-level multi-leader and/or multi-follower decision-making. These papers were selected according to three criteria: (1) novelty—published within the last decade; (2) impact—published in high quality (high impact factor) journals, or in conference proceedings or book chapters but with high citations; and (3) typicality—only the most typical methodologies were retained. These papers are mainly used in Section 2.

Step 4. Type 2 article selection. The techniques in relation to tri-level and multilevel decision-making, and fuzzy multilevel decision-making were analyzed and the related papers were selected according to the three criteria: (1) novelty,