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# Tri-level decision-making with multiple followers: Model, algorithm and case study

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ABSTRACT

Tri-level decision-making arises to address compromises among interacting decision entities distributed throughout a three-level hierarchy; these entities are respectively termed the top-level leader, the middle-level follower and the bottom-level follower. This study considers an uncooperative situation where multiple followers at the same (middle or bottom) level make their individual decisions independently but consider the decision results of their counterparts as references through information exchanged among themselves. This situation is called a reference-based uncooperative multi-follower tri-level (MFTL) decision problem which appears in many real-world applications. To solve this problem, we need to find an optimal solution achieving both the Stackelberg equilibrium in the three-level vertical structure and the Nash equilibrium among multiple followers at the same horizontal level. In this paper, we first propose a general linear MFTL decision model for this situation. We then develop a MFTL *K*th-Best algorithm to find an optimal solution to the model. Since the optimal solution means a compromised result in the uncooperative situation and it is often imprecise or ambiguous for decision entities to identify their related satisfaction, we use a fuzzy programming approach to characterize and evaluate the solution obtained. Lastly, a real-world case study on production-inventory planning illustrates the effectiveness of the proposed MFTL decision techniques.
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## 1. Introduction

Tri-level decision-making (also known as tri-level programming) technique has been developed to deal with decentralized decision problems involving interacting decision entities that are distributed throughout a three-level hierarchy, which is a subfamily of multilevel programming [30] motivated by Stackelberg game theory [26]. Decision entities at the three hierarchical levels are respectively termed the *top-level leader*, the *middle-level follower* and the *bottom-level follower*. The decision entities make their individual decisions in sequence, from the top level to the middle level and then to the bottom level with the aim of optimizing their respective objectives [36]. Specifically, the leader gives priority to making a decision; however, this decision is implicitly determined by the actions of the followers. The middle-level follower then reacts to the decision made by the leader and optimizes its own objective function while taking into account the implicit reactions of the

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bottom-level follower. Lastly, in view of the given decisions from the top and middle levels, the bottom-level follower makes decision to optimize its own objective function. The decision process is repeatedly executed until the Stackelberg equilibrium is achieved in the three-level vertical structure, which differs from the traditional Stackelberg game where the decisions made by the followers do not affect the decision, which has been already taken by the leader [11]. This category of the hierarchical decision-making process often appears in many decentralized management problems in applications, such as supply chain management [33], resource allocation optimization [20,34] and hierarchical production operations [29].

The hierarchical production-inventory planning in a conglomerate enterprise can be taken as an example. The conglomerate is composed of a sales company, a logistics center and a manufacturing factory, which are distributed throughout a three-stage supply chain. To fully satisfy market demand and shorten time-to-market, the sales company and the logistics center have to hold a certain amount of inventory using their respective warehouses but both of them nonetheless seek to minimize their individual inventory holding costs. When making the production-inventory plan within a stable sales cycle, the sales company (the leader) takes the lead in developing an optimal inventory plan which considers the current market demand and implicit reactions of other decision entities. The logistics center (the middle-level follower) then makes an optimal inventory plan under the decision given by the sales company and considers the implicit production planning of the manufacturing factory (the bottom-level follower). Lastly, the manufacturing factory makes the production plan to minimize its own cost of production in light of the fixed inventory plans. The decision process will not stop until the Stackelberg equilibrium among the decision entities is achieved. Consequently, the example describes a typical tri-level decision-making problem in which decisions are sequentially and repeatedly executed with all decision entities seeking to optimize their individual objectives until the Stackelberg equilibrium is achieved.

In general, there are two fundamental issues in supporting such a tri-level decision-making process. One is how to use a model to describe the decision-making process, which may manifest different characteristics at the three decision levels, and the other is how to find an optimal solution to the problem. Whereas the majority of studies on multilevel programming were focused on bi-level decision-making (also known as bi-level programming) such as in [3,5,9,10,12,14,17,31,35], research on tri-level decision-making has increasingly attracted investigations into decision models, solution algorithms and applications since it can be used to deal with many decentralized decision problems in the real world. Bard [4] first presented an investigation of linear tri-level programming and designed a cutting plane algorithm to solve such problems, based on which White [32] proposed a penalty function approach for linear tri-level programming problems. Faísca et al. [11] studied a multi-parametric programming approach to solve tri-level hierarchical and decentralized optimization problems. Yao et al. [34] built a tri-level optimization model for resource allocation in electric power network defense and proposed a decomposition approach to find an optimal solution to the model. Recently, Alguacil et al. [1] adopted a tri-level decision model to describe an electric grid defense planning problem and solved it using a novel two-stage solution approach. Street et al. [27] developed a tri-level decision model for energy reserve scheduling in electricity markets with transmission flow limits and found a solution to it by a Benders decomposition approach.

Although numerous studies have been carried out, existing tri-level decision-making research has been primarily limited to a specific situation in which one single decision entity is involved at each level. However, more decision entities are often involved at the middle and bottom levels in a tri-level decision-making case; these entities are called multiple followers. In the production-inventory planning example, the sales company (the *leader*) may have several subordinate logistics centers (the middle-level followers) and there may also be several manufacturing factories (the bottom-level followers) attached to each logistics center. Moreover, multiple followers at the same level may have a variety of relationships with one another. In our previous research [18], we developed 64 kinds of standard situations to describe various relationships within multi-follower tri-level (MFTL) decision problems, such as the uncooperative relationship, cooperative relationship, and semi-cooperative relationship. Such diverse relationships among multiple followers will generate different decision processes which need to be described and solved using different decision models and solution methods. As almost no research on MFTL decision-making has been proposed apart from some limited discussion about programming models [18,23], further investigation into MFTL decision models together with solution methods is necessary and urgent. Furthermore, MFTL decision techniques in real-world applications are crucially required.

This study considers an uncooperative situation where multiple followers at the same level make their individual decisions independently but exchange information among themselves, which implies that followers consider the decision results of their counterparts as references when making their individual decisions. The situation is known as a reference-based uncooperative (or reference-uncooperative) relationship, which is very common and popular among competitive or uncooperative decision entities in some hierarchical organizations. For example, in the proposed production-inventory planning instance, the independent logistics centers and factories may reference inventory or production plans determined by their counterparts at the same level when making their individual decisions. More specifically, within MFTL decision-making, if multiple followers at the same level determine their individual decision variables independently but simultaneously take the decision results of their counterparts for references to optimize their respective objectives, this can be called a reference-uncooperative MFTL decision problem. Solving this kind of MFTL decision problem implies that we need to find an optimal solution known as a *Stackelberg–Nash solution* to achieve not only the Stackelberg equilibrium in the tri-level vertical structure but also the Nash equilibrium among multiple followers at the same horizontal level. To support such a decision-making process, this paper will model this reference-uncooperative MFTL decision situation and find an optimal solution to the model.

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