项目调度多目标平衡分析模型及其应用

Xiangmu Diaodu Duomubiao Pingheng Fenxi Moxing Jiqi Yingyong

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全书对模糊环境下锦屏二级水电站太型建设工程项目调度问题的多目标决策模型及其应用进行了深入研究，设计了相应的算法并进行了分析讨论。

提出的四种模糊多目标决策优化模型将进一步丰富和发展不确定多目标决策理论、模糊理论和二层决策理论。

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前 言

由于社会的进步和经济的飞速发展，城市化进程加快，大型建设工程项目比比皆是，对能源的需求也急剧增加，如何发展清洁能源引起了大家的重视。为了发展清洁和可再生能源以及国家“西电东送”战略，中国正在建设大量的水电工程，尤其是在雅砻江流域。锦屏二级水电站是雅砻江上最重要的建设工程之一。然而由于锦屏二级水电站建设工程项目的规模巨大、参与要素众多、所需信息量大等因素影响，使其不确定性增强。对于传统多目标平衡项目调度问题，工期和成本是建设项目中非常重要的两个方面，但是锦屏二级水电站建设工程项目是一个生态建设工程，环境影响也是一个不可忽视的目标。其中，锦屏二级水电站工程建设项目多具有工程地质条件极其复杂、施工布置困难、总体规模大、综合难度大等特点，因而质量要求在某些分部工程中也是决策过程中不可缺少的管理目标。同时，在锦屏二级水电站建设工程项目中多项目调度计划的制订过程不可能由一个人完成，而是需要多层级决策人员共同参与并共同决策。因此，在考虑锦屏二级水电站建设工程项目多目标平衡的同时，可能还会考虑到结构多层次。可见，在锦屏二级水电站建设工程项目的调度问题中，应同时考虑模糊性、多目标性和多层次性这三种特性，不仅具有重要的理论意义，而且具有广泛的实践意义。

全书对模糊环境下锦屏二级水电站大型建设工程项目调度问题的多目标决策模型及其应用进行了深入研究，设计了相应的算法并进行了分析讨论。提出的四种模糊多目标决策优化模型，能够根据建设工程项目优化问题的实际情况制订出更加合理有效的调度计划，在缩短工期、降低成本、提高质量和减小环境影响等方面都具有积极的现实意义；同时，也将进一步丰富和发展不确定多目标决策理论、模糊理论和二层决策理论。本书的研究工作无疑将对模糊环境下多目标平衡项目调度决策问题的研究起到非常积极的推动作用。

本书共七章，其中第一章，主要介绍了本书的研究背景、研究现状以及研

究框架；第二章，主要介绍了与本研究相关的理论基础知识；第三、四、五、六章，主要介绍了四种模糊多目标决策优化模型及其求解算法；第七章，对全书进行了总结。

本书由郑欢提出研究思路，负责拟定编写大纲及写作框架，承担主要研究工作。本书各章具体编写分工如下：郑科撰写第一章；白海龙撰写第二、五、七章；郑欢撰写第三、四、六章以及摘要、参考文献等。郑科、白海龙同志参与了组稿工作并对部分内容进行了审定修改和校验。

本书的撰写是在四川大学长江学者徐玖平教授悉心指导下完成的，受国家自然科学基金委的支持，同时得到了四川二滩水电开发公司的大力支持。

因水平有限，书中难免有不妥和疏漏之处，敬请广大读者批评、指正。

郑欢

2013 年 6 月

摘 要

由于社会的进步和经济的飞速发展，城市化进程加快，大型建设工程项目比比皆是，对能源的需求也急剧增加，如何发展清洁能源引起了大家的重视。为了发展清洁和可再生能源及国家“西电东送”战略，中国正在建设大量的水电工程，尤其是在雅砻江流域。锦屏二级水电站是雅砻江上最重要的建设工程之一。然而对于锦屏二级水电站建设工程项目的规模巨大、参与要素众多、所需信息量大等因素影响，使其不确定性增强。对于传统多目标平衡项目调度问题，工期和成本是建设项目中非常重要的两个方面，但是锦屏二级水电站建设工程项目是一个生态建设工程，环境影响也是一个不可忽视的目标。其中，锦屏二级水电站建设地下深埋隧道群工程建设项目多具有工程地质条件极其复杂、施工布置困难、总体规模大、综合难度大等特点，因而质量在某些分部工程中也是决策过程中不可缺少的管理目标。同时，在锦屏二级水电站建设工程项目中多项目调度计划的制订过程不可能由一个人完成，而是需要多层级决策人员共同参与并共同决策。因此，在考虑锦屏二级水电站建设工程项目多目标平衡的同时，可能还会考虑到结构多层次。可见，在锦屏二级水电站建设工程项目的调度问题中，应同时考虑复杂模糊性、多目标性和多层次性这三种特性，不仅具有重要的理论意义，而且具有广泛的实践意义。

在现有的建设工程项目多目标平衡问题的研究中，同时考虑复杂模糊性、多目标性和多层次性的研究还比较少。为此，在广泛地吸收和借鉴现有研究的基础上，以锦屏二级水电站建设工程项目中的多目标平衡项目调度问题为研究对象，模糊变量为研究工具，多目标模型为研究框架，综合运用多目标规划理论与优化理论，对模糊环境下的锦屏二级水电站建设工程项目优化问题进行研究，建立了四种不同决策条件下的模糊环境下多目标平衡项目调度问题模型。

首先，结合经典离散工期－成本平衡问题（discrete time－cost trade－off prob－lem，DTCTP）的现有研究，由于大家对环境问题的重视，提出了针对

锦屏二级水电站建设工程项目的离散工期－成本－环境平衡问题（DTCETP），是对DTCTP的一个拓展，同时在考虑工期为模糊变量，建立了模糊环境下大型建设项目管理中的多模式离散工期－成本－环境平衡的问题模型。其有四个目标需要考虑：最小化项目总费用、最小化项目总工期、最小化总压缩费用、最小化环境影响。在总预算、资金流以及工期都有一定的约束下，工程中的每个活动可以增加费用以压缩工期方式进行，同时需考虑环境影响最小化的目标对施工模式的影响，这就形成了多模式选择的决策问题。在利用乐观－悲观参数期望值模型将模糊变量进行确定化处理后，模糊环境下大型建设项目管理中的多模式离散工期－成本－环境平衡的问题模型便转化为多目标期望值模型，分析了该问题求解的意义，并用改进的遗传算法——基于模糊的适应性混合遗传算法［fuzzy－based adaptive hybrid genetic algorithm〈（f）a－hGA〉］来求解。当该多目标模型为线性时，可直接用期望值模型来求解；当该模糊多目标模型为非线性时，无法直接求出其期望值时，则通过模糊模拟植入适应性混和遗传算法来求解模型。然后，通过加权法将多目标模型转化为单目标，即求解单目标期望值模型。［（f）a－hGA］设计了单点交叉和变异的修复式策略来避免不可行解的产生。基于此，将该算法用来解决二滩公司锦屏二级水电站建设部分工程调度的问题，得到了最佳调度计划和最优施工模式，而且从实际角度分析了结果，拓展了结果的应用范围，从而验证了模型和算法的可行性和有效性。此外将（f）a－hGA与其他两种GA算法（GA、hGA）进行了比较，验证了所提出算法的先进性。

其次，考虑了锦屏二级水电站建设地下深埋隧道群工程建设项目多具有工程地质条件极其复杂、施工布置困难、总体规模大、综合难度大等特点，施工质量是建设安全和顺利进行的重要保障。基于大型建设工程项目其项目量大、短工期、高质量、低环境影响的要求，研究了锦屏二级水电站大型深埋隧道群工程的多模式离散时间－成本－质量－环境平衡问题（discrete time－cost－quality－environment trade－off problem，DTCQETP）的多目标优化模型，这是对前一段离散工期－成本－环境平衡问题（DTCETP）的拓展。针对DTCQETP的四个目标做出了分析：最小化项目工期、最小化项目总成本、最小化质量缺陷、最小化环境影响。在总预算、资金流、工期以及每个阶段质量缺陷和环境影响都有一定的约束下，为每个活动选择合适的施工模式以及安排最优的调度计划。通过将模糊变量精确化的处理，将DTCQETP转化为多目标期望值模型，并用改进的遗传算法——基于模糊的适应性混合遗传算法（f）a－hGA来求解。

该算法中应用了基于次序的交叉和局部变异来提高算法求解效率，其用来解决实际的锦屏二级水电站大型深埋隧道群工程这个项目的调度问题，得到了最佳调度计划和最优施工模式，通过和实际运作的数据对比，建设效率取得明显进步，说明该优化方法可以带来可观的经济效益，尤其是对于大型建设工程项目。从实际角度分析了结果，拓展了结果的应用范围，从而验证了模型和算法的可行性和有效性。此外将（f)a－hGA与其他两种GA算法（GA、hGA）进行了比较，验证了所提出算法的先进性。

再次，考虑了锦屏二级水电站建设工程项目中多项目运作的问题。提出了基于总承包商的多项目时间－成本－环境平衡调度问题（multiple projecttime－cost－environment trade－off scheduling problem，mPTCETSP），主要针对项目规模较大、结构较复杂的问题，也是经典多目标平衡调度问题的扩展，建立了模糊环境下的时间－成本－环境平衡多项目调度问题期望值模型。目标是：所有子项目工期之和最小、整个项目延期惩罚成本最小或者工期提前奖励最多、整个项目造成的环境影响最小。项目施工每个阶段的各子项目的各活动总费用不能超过规定子项目资金流量最大值且各阶段所有进行活动的资金总值也不能超过总限定值；同时，项目施工每个阶段监测的各子项目的活动环境影响总值不能超过限定值并且各阶段所有进行活动的环境影响总值也不能超过总限定值，在这样的约束条件下，求解最优调度计划的决策问题。利用乐观－悲观参数期望值模型将模糊变量进行确定化处理后，模糊环境下大型建设项目管理中的多项目时间－成本－环境平衡多目标调度问题便转化为多目标期望值模型。模糊多目标模型为非线性时，将对模型中带有模糊变量的参数进行模拟计算，并结合多目标GA算法（MOGA），设计了混合智能算法——FLC设计遗传算子的混合遗传算法（hybrid genetic algorithm with a fuzzy logic controller，flc－hGA）来求解模糊环境下的mPTCETSP，特别适用于大型多项目调度问题。该算法引入的模糊控制器（fuzzy logic control，FLC）提供了一种基于专家知识，能将语言控制策略转化为自动控制策略的方法，用以规范变异率。然后，通过模糊环境下的多项目时间－成本－环境多目标调度问题期望值模型和flc－hGA来解决锦屏二级水电站建设系统中的部分多项目多目标调度问题，得到了最佳调度计划，并对最佳调度计划进行了结果分析和灵敏度分析，得出了一些有益于实际操作的结论，验证了模型和算法的可行性和有效性。flc－hGA与其他GA（hGA、a－hGA）进行比较分析的结果表明，flc－hGA的适应值、收敛代数及运行时间均较优。

最后，研究了多项目时间－成本－质量－环境平衡调度问题（multiple project time－cost－quality－environment trade－off scheduling problem，mPTCQETSP），在锦屏二级水电站大型建设工程项目调度问题的决策过程中，由于规模较大、施工复杂，在制订项目调度计划时往往需要考虑多个决策目标和多个决策层次结构。基于此，结合模糊理论和二层规划，建立了上下层均为多目标的模糊环境下多项目时间－成本－质量－环境平衡调度问题模型。上层决策者（项目总指挥）的目标是项目总的完成质量最高以及环境影响最小，下层从属决策者（项目经理）的目标是子项目的完成时间最小、惩罚费用最少和综合费用最少。在精确化后的模型中，用交互式模糊规划技术将mPTCQETSP的二层规划模型转化为单层规划模型。因为在作决策时，项目总指挥不仅要考虑自己的满意度，而且要考虑各项目经理的满意度，然后用熵－玻尔兹曼选择遗传算法求解该单层模型。通过二层模糊期望值模型、交互式模糊规划技术以及熵－玻尔兹曼选择遗传算法（EBS－based GA）来解决锦屏二级大型水电站建设项目中部分项目的调度问题，以及项目最佳调度计划和子项目中每个活动的最佳调度方式，其考虑了项目组织多方满意度的平衡，保证了项目长期和短期的利益，和实际运作效果相比，验证了该优化方法的可行性和有效性。

全书对模糊环境下锦屏二级水电站大型建设工程项目调度问题的多目标决策模型及其应用进行了深入研究，设计了相应的算法并进行了分析讨论。提出的四种模糊多目标决策优化模型能够根据建设工程项目优化问题的实际情况制订出更加合理有效的调度计划，在缩短工期、降低成本、提高质量和减小环境影响等方面都具有积极的现实意义；同时，也将进一步丰富和发展不确定多目标决策理论、模糊理论和二层决策理论。本书的研究工作无疑将对模糊环境下多目标平衡项目调度决策问题的研究起到非常积极的推动作用。

关键词：模糊变量　多目标规划　锦屏二级水电站大型建设工程项目　遗传算法　期望值　乐观－悲观值

ABSTRACT

In recent years, as China has experienced rapid growth in both the economy and society, the need for energy has also exponentially grown. New and renewable sources of energy have become more important and consequently hydropower resources have also become more important. In order to develop clean and renewable energy sources, a number of large scale hydropower projects are being constructed in China for achieving West - East Electric Transmission Project, especially on the Yalong River Valley. The Jinping - II Hydropower Station is one of the most important projects in the Yalong River Valley. The Jinping - II Hydroelectric Project is one of EHDC' s projects under construction. However, as the complex large - scale project involving more and more elements and greater amount of information in Jinping - II Hydroelectric Project, therefore, there are uncertainties in the trade - off problem for project scheduling because of suffcient information. Time and project cost are crucial aspects of construction projects and have received significant attention for several years in traditional multi - objective trade - off problem for project scheduling. Environm ental impact should be taken into consideration along with the time and cost trade - offs in Jinping - II Hydro - electric Project because more than one billion yuan for environmental protection has been allocated for the project, and control measures and construction environm ental criteria for the project have been proposed to coordinate with the other objectives. The large - scale deeply - buried tunnel group project, which is one

of the most important subprojects in Jinping – II Hydropower Station, is the largest and most difficult hydro – tunnel project in the world, so quality is important for asecure and smooth construction and quality have been proposed to coordinate with the other objectives. The process of multi – objective trade – off problem for project scheduling decision making can not be determined by a manager, but multi – level decision – makers. Hence, besides mul – tiple objectives, the multi – level structures should be optimized in the multi – objective trade – off problem for project scheduling. Therefore, the discussion of multi – objective trade – off problem for project scheduling in Jinping – II Hydroelectric Project getsnot only specific theoretical but also practical significance.

At present, there is no literature which takes multi – objective, fuzziness and multi – level into account for multi – objective trade – off problem for project scheduling. In this dissertation, after sum marizing the existing literatures, this paper will take a challenge to present four multi – objective trade – off problem in project scheduling models under fuzzy phenomena, the corresponding and the hybrid intelligent algorithm, and the application to the Jinping – II Hydropower Station.

First of all, combining the classic (discrete time – cost trade – off problem, DTCTP), a discrete time – cost – environment trade – off problem (DTCE TP) for Jinping – II Hydroelectric Project with multiple modes under fuzzy uncertainty is presented due to environm ental protection, an extension of DTCTP. A multi – objective decision making model is established in which the total project duration is regarded as a fuzzy variable. In this paper, four objectives for the DTCE TP are considered: the minimization of the total projectcost, the minimization of the total project duration, the minimization of the total crashing cost, the minimization of the environmental impact. This paper considers that construction managers need to develop a project management methodology for directing and controlling not only the total projectcost, duration and cash flow, but also the environ-

mental impact to achieve management objectives, every activity can be executed in the crashing way, duration/cost/environment of an activity is determined by the mode selection and the duration reduction (crashing) applied within the selected mode. This leads to a multiple modes discrete time - cost - environment trade - off problem (DTCETP). To deal with the uncertainty, the fuzzy numbers in the model are defuzzified by using an expected value operator with an optimistic - pessimistic index. Furthermore, a fuzzy - based adaptive - hybrid genetic algorithm is developed to find feasible solutions. The algorithm proposed here has two modes for linear and non - linear situations, respectively. In the linear case, the fuzzy expected value model (EVM) is embedded in the a - hGA to deal with the fuzzy variables that are in linear functions, while in the non - linear case, the fuzzy simulation is combined with a - hG A for han - dling the nonlinearity of the fuzziness. The weighting method is applied to transform the multi - objective model into a single - objective one. The one - point crossover and repairing strategy for mutations are designed to avoid infeasible solutions. Finally, the Jinping - II Hydroelectric Project is used as apractical example to demonstrate the practicality and efficiency of the model. Results and a sensitivity analysis are presented to highlight the performance of the optimization method, which proves to be very effective and efficient compared to other algorithms.

The large - scale deeply - buried tunnel group project, which is one of the most important subprojects in Jinping - II Hydropower Station includes, four diversion tunnels, two auxiliary tunnels and one drainage tunnel, with a total tunnel length of 118 km. These tunnels are long, are large in diameter, need to endure high stress, and encompass complicated engineering geological conditions such as water bursts, rock bursts, and collapses. Because this tunnel project is the largest and most difficult hydrotunnel project in the world, these conditions are extremely difficult for effective project management. Therefore, quality is important for a secure and smooth construction. So it studies a multi - objective op-

timal model for solving a discrete time – cost – quality – environment trade – off problem (DTCQETP) with multiple modes for the large – scale deeply – buried tunnel group project in Jinping – II Hydropower Station. It is an extension of DTCETP. The objective functions that minimizes the project duration, cost, quality defects and environmental impact are presented. To achieve the optimal scheduling and executive mode, the DTCQETP analysis, with uncertain activity duration and environmental impact, under the constraints of project due dates, within budget, cash flow, quality defect level and environmental impact in each time period. The fuzzy EVM technique is used to defuzzify the fuzzy durations and environmental impact. The weight – sum procedure is adopted to transform the multi – objective model into a single – objective model. The solution is composed of two chromosomes for the DTCQETP where the first chromosome shows the feasible activity sequence and the second chromosome consists of activity mode assignments. Order – based crossover (OBX) and a local searchbased mutation are used in this (fuzzy – based adaptive hybrid genetic algorithm ((f)a – hGA)) which is solved DTCQETP in the large – scale deeply – buried tunnel group project in Jinping – II Hydr opower Station. Finally, the large – scale deeply – buried tunnel group project in Jinping – II Hydropower Station is used as a realworld example to demonstrate the economic, technological, and social ecological effectiveness of the optimization method.

Subsequently, with multi – objective trade – off problem for project scheduling in Jinping – II Hydropower Station which are split into several sub – projects, it studies the multiple project time – cost – environment trade – off scheduling problem, (mPTCETSP) and establishes the expected value model for mPTCETSP under fuzzy uncertainty for large – scale and more complex problem. It is an extension of classic multi – objective trade – off problem. The objective functions are pursuing the minimum duration, the minimum tardiness penalty and minimum environmental impact. The sum of the capital or the environmental impact of the

activities in all subproject which are scheduled in a certain time period during the whole project duration cannot exceed the capital or environmental impact limit per time period. Achieve the optimal project scheduling under these constraints. After defuzzifying fuzzy numbers in the model by using an expected value operator with an optimistic—pessimistic index, the multi - objective expected value model combines with hybrid genetic algorithm with a fuzzy logic controller (flc - hGA) to solve mPTCETSP. FLC can adaptively regulated the GA parameters based on experts' knowledge. The effectiveness of the proposed model and algorithm is proved by a practical application in Jinping - II Hydropower Station. The results of comparative analysis between the proposed flc - hGA and other GA algorithm indicate that flc - hGA has more prominent performances in the fitness value, the convergence iterations and the elapsed time.

Finally, we consider a four - dimensional time - cost - quality - environment trade - off problem which are split into several sub - projects, and present a bi - level multi - objective multiple project scheduling models under fuzzy phenomena which has multiple upper objectives and multiple lower objectives. The upper objectives are minimizing the quality defect and environmental impact, and the lower objectives are minimizing the duration, tardiness penalty, and comprehensive cost in their subproject. To solve the bi - level multi - objective models, the weight - sum procedure is adopted to transform the multi - objective model into a single - objective model at first, then interactive fuzzy programming technique is used bi - level model into a single - level model. At last, EBS - based GA is utilized. The superiority of the proposed hybrid intelligent algorithm is proved by comparison with the other GA algorithm.

Above all, multi - objective decision model and bi - level multi - objective decision model in Jinping - II Hydroelectric Project is deeply studied and accordingly algorithms for solving the proposed problems are analyzed. The proposed four multi - objective decision making optimization models under fuzzy environ-

ment can develop a more reasonable and effective decision scheduling based on the practical situation of Jinping – II Hydroelectric Project for minimizing the duration, cost, quality defect and environmental impact. Undoubtedly, in the future research, this dissertation will be contributed in multi – objective and bi – level decision making under complex phenomena and complex large – scale project scheduling problems.

Key words: Fuzzy variable, Multi – objective programming, Jinping – II Hydroelec – tric Project, Genetic Algorithm, Expected value, Optimistic – pessimistic index.

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