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考虑维护时间的机器调度问题研究

RESEARCH ON MACHINE SCHEDULING PROBLEMS WITH CONSIDERATION OF PREVENTIVE MAINTENANCE

马　英/著　杨善林/导师

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马 英 著　　杨善林 导师　　责任编辑 权 怡　　责任校对 刘 露

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摘　要

传统的机器调度问题通常假定在整个调度期内机器一直可用。然而，在实际生产过程中，为了避免因机器失效或机器故障而导致的产品质量下降、维护成本增加和生产效率降低等问题，企业一般都会在调度期之前预先安排机器维护，因此在调度问题中考虑这种预防维护时间更具现实意义。

本书首先较为详尽的研究了考虑维护时间的单机调度问题，包括维护时段固定且加工时间恒定、维护时段固定且加工时间可变、维护时段可调且加工时间恒定以及维护时段可调且加工时间可变等四类问题。对于多机调度问题，重点研究了维护时段固定且加工时间恒定的问题，以此说明了把单机调度问题的求解方法拓展到相应多机调度问题的思路，其他三类问题均可按照这种思路进行求解。受维护时段的影响，工件在加工过程中可能会被中断，基于实际生产过程中的不同情况，本书分别考虑了被中断工件可续、不可续和部分可续三种情形。

上述问题的目标函数假定为与生产效率有关的最大完工时间及(加权)完工时间和。根据问题的复杂性不同，本书给出了不同的求解方法：对于NP-难问题，本书一方面致力于设计能求解尽可能大规模问题的精确算法；另一方面，鉴于精确算法在时间和空间性能上的不足，本书也致力于构造高效的启发式算法，从而能够在合理的时间内求得大规模问题的高质量的满意解。另外，在某些特殊情形下，有些问题是多项式可解的，对于这些问题，本书通过证明某种多项式时间算法能够为其提供最优解来说明其多项式可解性。

具体而言，本书的主要研究内容和创新点如下：

(1)对于维护时段固定且加工时间恒定的单机调度问题，研究了部分可续情形下的两种目标函数。对于最大完工时间最小化问题，简单说明了此

问题的 NP-难性，给出了最大加工时间优先（Longest Processing Time first，LPT）规则的最坏情况相对误差界，进而提出了两个基于 LPT 规则的启发式算法：LPT-PI 和 MLPT，其中 LPT-PI 以 LPT 规则作为初始解，并结合基于成对交换技术的邻域搜索对解进行改进，而 MLPT 通过改进 LPT 算法执行过程中的某一类特殊情况来得到更优的启发式解。另外，还证明了 MLPT 的最坏情况相对误差界，并通过大规模实验对算法性能进行了对比分析。对于加权完工时间和最小化问题，简单说明了问题的 NP-难性，提出了最优解的性质，并在此基础上构造了动态规划和分枝定界两种精确算法。大量随机数据的实验结果表明这两种算法都是有效的，且不论从能解问题规模，还是从寻得最优解所需时间方面，分枝定界算法都要优于动态规划算法。

(2)对于维护时段固定且加工时间可变的单机调度问题，研究了最大完工时间及完工时间和两种目标函数。证明了这两种目标函数下加工时间线性增加和线性减少时的几种可续情形是多项式可解的。对于不可续情形，重点研究了加工时间线性增加时的最大完工时间问题。对于该问题，简单说明了其 NP-难性，证明了最优解的性质，在此基础上构造了一种动态规划算法，鉴于此算法应用上的局限性，给出了 SNPT（Shortest Normal Processing Time）规则的最坏情况相对误差界，进而提出了一种基于 SNPT 规则和交换技术的启发式算法。大量算例的实验结果显示，不仅算法的运行时间很少，其相对误差也很小（平均相对误差和最大相对误差分别为 0.082% 和 3.448%），并且将近有一半的算例能得到最优解，因此该启发式算法能够很高效的解决此类问题。而对于其他目标函数和加工时间函数下的不可续情形，通过分析与上述问题求解方法上的相似性，给出了其求解思路。

(3)对于维护时段可调的单机调度问题，重点研究了加工时间恒定的问题，考虑了完工时间和这个目标函数。对于可续情形，给出了最优解的几个性质，提出了一种 SPT 算法，并证明了其最优性；对于不可续情形，简单说明了其 NP-难性，提出了几个与可续情形类似的最优解的性质和 SPT 算法，给出了该算法最优的条件，并证明了其最坏情况相对误差界。在最优解性质的基础上，构造了一种动态规划算法和一种分枝定界算法，其中分枝定界

算法的初始解是在SPT算法的基础上利用两条性质对维护时段之前的末工件和维护时段之后的工件进行交换所得，而提出的几个下界是基于维护时段固定的相应问题。实验证明了动态规划和分枝定界这两种算法的有效性及互补性。对于加工时间可变的调度问题，首先证明了其可续情形是多项式可解的，并对此问题与相应加工时间恒定问题在求解方法上的相似性进行了总结，进而给出了不可续情形的求解思路。

(4)对于多机调度问题，重点研究了维护时段固定且加工时间恒定的问题，考虑了部分可续情形下的两种目标函数。对于最大完工时间最小化问题，说明了问题的NP-难性，建立了整数规划模型，并提出了两台机器上工件互换的四条性质，进而提出了一种启发式算法，该算法首先把所有工件按LPT算法进行分配，得到一个可行解，然后再重复把最大完工时间最大和最小两台机器上的工件进行互换以提高解的质量。该启发式算法和LPT算法的对比实验结果验证了此算法的有效性；对于加权完工时间和最小化问题，说明了问题的NP-难性，给出了最优解的性质，进而提出了一种动态规划算法来求得中小规模问题的最优解，另外还提出了一种基于WSPT(Weighted Shortest Processing Time)规则和交换技术的启发式算法来解决大规模问题，实验结果表明启发式算法的平均相对误差为0.463%，最大相对误差也仅为5.094%，因此该算法不失为一种比较有效的启发式算法。在此基础上，通过比较这两个问题与相应单机问题求解方法上的异同，给出了如何把单机问题的求解方法推广到相应多机问题的思路，按照这种思路，其他的三类多机问题即可得到解决。

关键词：机器调度；预防维护；动态规划；分枝定界；启发式算法

Abstract

In classical scheduling models, it is usually assumed that machines are always available for processing throughout the whole scheduling period. However, in real industry settings, manufacturers usually plan preventive maintenance in advance before the scheduling period as machine failure or breakdown should be prevented to guarantee products quality, reduce maintenance costs and improve production efficiency. In this regard, it is necessary to consider such preventive maintenance in scheduling problems.

In this dissertation, single machine scheduling problems with consideration of preventive maintenance are considered in detail firstly, which include the problems with a deterministic maintenance and constant jobs, the problems with a deterministic maintenance and deteriorating jobs, the problems with a flexible maintenance and constant jobs, and the problems with a flexible maintenance and deteriorating jobs. For the multi-machine scheduling problems, the emphasis lies in the problem with a deterministic maintenance and constant jobs, based on which, the idea to extend the method for single machine problem to the corresponding multi-machine problem is introduced, and with this idea, the other three multi-machine problems can be solved in a similar way. Affected by maintenance periods, jobs may be interrupted during processing. In view of the different case in real industry, three cases, i. e., resumable, nonresumable and semi-resumable cases are considered in this dissertation.

It is assumed that the objective functions of these problems are makespan and total (weighted) completion time, both of which are related

to production efficiency. According to the complexity of the problems, different methods to generate solutions are applied: for the NP-hard problems, on one hand, exact algorithms are developed to derive an optimal solution for the problem within a reasonable size, on the other hand, in view of the deficiency of these exact algorithms, effective heuristics are proposed to obtain a near-optimal solution for the large-sized problem within a reasonable time period; in some special cases, the problem is polynomially solvable, which is proved by the fact that a polynomial algorithm can generate optimal solutions for such a problem.

The main contributions of the dissertation are summarized as follows.

(1) For the single machine scheduling problems with a deterministic maintenance and constant jobs, two objective functions are considered as follows with the assumption that the disrupted job is semiresumable: A) For the makespan minimizing problem, after a brief explanation of the fact that the problem is NP-hard, the worst-case relative error bound of the LPT rule is analyzed, based on which, two heuristics, i. e. , LPT-PI and MLPT, are proposed. Specifically, LPT-PI considers the LPT rule as the initial solution, which is then improved by a neighborhood search based on Pairwise Interchanges; while MLPT improves the LPT algorithm when a class of special cases happens. In addition, the worst-case relative error bound of the MLPT is also shown. To compare the performance of LPT-PI and MLPT, a large number of experiments with random data are conducted. B) When the objective is to minimize the total weighted completion time, it is easily shown that the problem is NP-hard. Then, a property of the optimal solution is proposed, based on which, a dynamic programming algorithm and a branch-and-bound algorithm are developed. Experiment results show that the algorithms are effective, and that the branch-and-bound outperforms the dynamic programming in both the size of the problem solved and the time needed to find the optimal solution.

(2) For the single machine scheduling problems with a deterministic

maintenance and deteriorating jobs, two objective functions, i. e., the total completion time and the makespan, are considered. When the disrupted job is resumable, the problems with linear increasing or linear decreasing processing times under the two different objectives mentioned above are shown to be polynomially solvable. As for the nonresumable case, the problem with linear increasing processing times with respect to minimize the makespan is considered in detail. For such a problem, its NP-hardness is briefly discussed and then, a property of the optimal solution is proposed, based on which, a dynamic programming algorithm is developed to derive the optimal solution. Due to the limitations of the algorithm in its application, the worst-case error bound of the Shortest Normal Processing Time (SNPT) rule is given. Based on the SNPT rule and interchange technique, a heuristic is proposed to find the near-optimal solution. Experiment results show that the heuristic is excellent not only in its running time but also in the quality of solution, as regarding all the instances, the average and maximum relative error between the results generated by the heuristic and those genertated by dynamic programming are only 0.082% and 3.448% respectively, in addition, the solution is optimal for almost half of the instances in the experiments. Further, the analysis shows that there are similarities between the methods solving the problems mentioned above and the methods solving the problems under other objectives and processing time functions, and such methods are also given in the dissertation briefly.

(3) For the single machine scheduling problems with a flexible maintenance, the emphasis lies in the problem with constant jobs, in which the total completion time is minimized. For the resumable case, a set of properties of the optimal solution are identified first. Then an SPT algorithm is proposed and the solution generated by the algorithm is shown to be optimal, which implies that the problem is polynomially solvable. As for the nonresumable case, its NP-hardness is explained briefly. Similar to

the resumable case, a set of properties of the optimal solution and a SPT algorithm are presented. Additionally, the conditions under which the SPT algorithm is optimal are also specified. Furthermore, the relative error bound of the SPT algorithm is provided as well. Based on the properties of the optimal solution, a dynamic programming and a branch-and-bound algorithm are developed. For the branch-and-bound algorithm, its initial solution is based on the SPT algorithm, then, such a solution is improved by swapping the last job before the maintenance with jobs after the maintenance according to the two new properties proposed; in addition, the proposed lower bounds are generated based on the corresponding problems with deterministic maintenance. Experimental results show that the dynamic programming and the branch-and-bound algorithm are effective and complementary in dealing with different instances of the problem. And for the problem with deteriorating jobs, its resumable case is shown to be polynomially solvable, then the similarity between the methods to solve the problem with deteriorating jobs and the corresponding one with constant jobs is discussed, based on which, the method to solve the nonresumable case is given.

(4) For the multi-machine scheduling problems, the focus is the problems with deterministic maintenances and constant jobs. With the assumption that the disrupted job is semiresumable, two objectives, i. e., minimizing the makespan and minimizing the total weighted completion time, are considered as follows: A) For the problem to minimize the makespan, its NP-hardness is explained firstly. Subsequently, an integer programming model is developed, and four properties of swapping jobs between two machines are introduced. Based on the properties, a heuristic is proposed, which takes the LPT schedule as its initial solution and improves the solution by repeatedly swapping the jobs between two machines with the maximal and minimal makespan respectively. Experiment results regarding the comparison between the heuristic and the LPT algorithm show that the

proposed heuristic is efficient and effective. B) For the problem to minimize the total weighted completion time, following the discussion of the problem's NP-hardness, a property of the optimal solution is proposed. Based on the property, a dynamic programming algorithm is developed to derive the optimal solution for the small-sized problems. Additionally, a heuristic based on the WSPT rule and interchange technique is proposed to obtain the near-optimal solution for the medium-to-large-sized problems. Experiment results show that the average and the maximum relative error of the heuristic are 0.463% and 5.094% respectively, which indicate the effectiveness of the heuristic. After the analysis of the difference and similarity between the methods to solve the above two problems and the corresponding single machine problems, the idea to extend the method for single machine problem to multi-machine problem is introduced. With this idea, the other three multi-machine problems can be solved accordingly.

Keywords: Machine scheduling; Preventive maintenance; Dynamic programming; Branch-and-bound; Heuristic

目　　录

第1章 绪 论

在研究传统的机器调度问题时一般假设机器在整个调度期内都是可以连续加工的，但在企业的实际生产过程中，为了降低机器失效率进而减少机器故障，对机器进行维护是必不可少，因此在对机器调度的同时应考虑对机器维护的影响。本书研究的就是此类带维护时间的调度问题。本章首先分别对传统的调度问题和企业生产过程中的预防维护进行介绍，说明在调度问题中考虑预防维护的重要性，然后对此类问题的分类及符号表示进行简单的说明，最后给出全文的章节安排。

1.1 传统的机器调度问题

机器调度问题(Machine scheduling)是一类重要的组合优化问题，被广泛应用于机械制造、计算机系统、生产管理等领域。在现代企业中，机器调度问题已成为提高资源利用率进而提高企业运行效益的关键环节之一，是制造系统运筹技术、管理技术与优化技术发展的核心。有效调度方法的研究和应用，已成为先进制造技术实践的基础和关键，因此对它的研究具有十分重要的理论价值和现实意义。

机器调度问题主要研究如何利用一些机器或资源，在需要满足某些限制条件的情况下，最优地完成一批给定的任务或作业，这些限制条件包括任务的到达时间、完工的限定时间、任务的加工顺序、资源对加工时间的影响等。最优地完成是指使目标函数达到最大或最小，而目标函数通常是对加工时间长短、机器利用率高低等的描述。

1.1.1 发展简史

跟运筹学其他应用领域一样，调度理论研究始于 20 世纪 50 年代早期。根据研究的侧重点不同，对调度问题的研究大体可划分为三个主要阶段[1]：

第一阶段：20 世纪 50 年代到 60 年代，研究简单调度问题的有效最优算法和精确算法，经典调度理论框架形成。

这一阶段，人们为一些简单的调度问题找到了一些有效的最优算法。典型的有：Johnson 算法、EDD（Earliest due date）规则、WSPT（Weighted shortest processing time）规则和 Moore - Hodgson 算法，这些算法直至现在仍然是许多算法的基础，其中 1954 年 Johnson 的论文[2]被普遍认为是经典排序的第一篇文献。随后，人们开始了对精确算法的研究，如混合整数规划、动态规划以及分枝定界算法等，并且人们也开始用启发式算法求解一些常规方法难于求解的问题，如 Palmer 算法、Giffler 算法和 Fisher 算法。至此，经典调度理论的框架已经形成。

第二阶段：20 世纪 70 年代，开展调度问题的复杂性分析并进行启发式算法及其有效性研究，经典调度理论形成。

20 世纪 70 年代初，人们开始注意并重视计算复杂性理论，并依据计算复杂性对排序问题进行分类，发现除为数不多的问题具有多项式时间算法（P）外，大部分问题都是 NP -难（NP - hard）的。对于这些问题，有效最优算法是不存在的，于是人们的重点转向了启发式算法及其有效性的研究，并取得了丰硕的成果。

第三阶段：20 世纪 80 年代至今，调度环境、目标的多样化、复杂化和实际化，求解方法的通用性、实用性研究。

随着现代工业的发展，人们逐渐认识到之前对于调度问题的研究附加了过多的脱离实际环境的假设，并且目标函数过于简单，而这些已经严重制约了调度理论的研究深度和实际应用范围。因此人们开始倾向于研究具有更复杂、更接近于实际的调度目标函数和制造环境下的调度问题。同时，智能优化方法和人工智能技术的兴起也为求解这些复杂的调度问题提供了有效的工具。如不仅模拟退火算法（Simulated Annealing，SA）、遗传算法（Genetic Algorithm，GA）、蚁群算法（Ant Colony Algorithm，ACA）、神经网