The Sequence Dependent Machine Set-Up Problem: A Brief Overview.

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ABSTRACT

The Sequence Dependent Machine Setup Problem (MSP), a class of difficult problems in combinatorial optimization that is representative of a large number of important scientific and engineering problems, has been attracting much attention in recent times. In this study, literature and historical reviews of the MSP were carried out. Some recent developments were reviewed while possible future research directions were also highlighted.

(Keywords: MSP, machine set up problem, traveling salesman problem, combinatorial optimization, engineering principals)

INTRODUCTION

The sequence dependent Machine Setup Problem (MSP) is the problem of determining an optimal sequence that a set of N operations will be performed by a general purpose facility in order to minimize the total cost or time of re-setting the facility. The setup time is defined as the time intervals between the finishing of a job and the beginning of the next job. In a single machine scheduling problem, with all jobs j=1,2,3….,N having the same ready time (i.e. a static scheduling environment) and no sequence-dependent setup times, the maximum completion time or the makespan C_{max} is independent of the sequence and equal to the sum of the processing times of the N jobs. However, in many realistic problems there are sequence dependent setup times and in such situations C_{max} is a function of the schedule.

The scheduling problem of optimizing the makespan or C_{max} on a single machine with sequence-dependent machine setup times S_{ij} (setup time if job j is processed immediately after job i) is the single Machine Setup Problem. Given N parts and a processor, an MSP algorithm finds the order (a sequence of the N parts) in which each part will pass through the processor or the processor will pass through each only once, so that C_{max} is minimized.

Note that MSP's rendition as a processor passing through the N parts (stations) is popularly interpreted as the Traveling Salesman Problem (TSP). The TSP can be stated thus "Given N cities and the distance or cost between each pair of cities, a salesman starting in one city wishes to visit each of N-1 other cities once and only once and return to the starting point. In what order should he visit the cities to minimize the total distance traveled?" (See Deıˇneko et al., 2006; Gutin and Punnen, 2002; Lawler et al., 1985; Kahng and Reda, 2004; Balas and Simonetti, 2001; Charles–Owaba, 2001; Dantzig, 1954; and Little et al., 1963).

When $S_{ij}=S_{ji}$ the problem is a special case, the Symmetric TSP (STSP). However, the Machine Setup Problem (MSP) is actually the equivalence of the more general Asymmetric TSP (ATSP), thus the MSP is really the scheduling term for the TSP (see Pinedo, 1995; Charles-Owaba, 2001). Therefore the terms MSP and TSP will be interchangeably used in this paper.

The Asymmetric TSPs or MSPs cases have been shown to be more difficult to solve than their symmetric equivalent with respect to both optimization and approximation (Johnson et al., 2002; Zhang 2004; Oladokun, 2006). Also, most of the works reported in the literature deal with the STSP and are mostly referred to as TSP (see Gutin and Punnen, 2002; Applegate et al., 2004; Walshaw, 2002). There have been indeed very few studies on the MSP or the ATSP (Kwon et al., 2005) reported in the literature.

Presently, the major difficulty in the use of existing algorithms arises from computing time requirements. The time requirement of published methods increases exponentially with the problem size. Most large problem instances solved to optimality have been solved, using super computers or massively parallel computer processors. For instance, the largest instance of the TSP solved to optimality is the 24,978 Sweden cities carried out on a cluster of 96 Intel Xeon 2.8 GHz dual-processor machines requiring an equivalent estimated time of 91.9 CPU years of a single Intel Xeon 2.8 GHz processor. The computation started in March 2003 and finished in May 2004 (Applegate, 2004).

Unfortunately, super computing and massively parallel computing are often not available for industrial applications, where interest in MSP algorithms is fast growing (Charles–Owaba, 2001; Charles–Owaba, 2002; Rajkumar and Narendran, 1996; Radin, 1998).

Implicit enumeration and heuristics are the traditional solution approaches. The former are inefficient, therefore impractical for industrial applications, while the later are efficient but many lack effectiveness. For instance there are 2.4 x 10^{18} and 1.5 x10^{25} possible solutions for a 20 parts problem and 25 parts problem respectively.

IBM built the 280.6 teraflop Blue Gene/L supper computer which could perform up to 280.6 trillion calculations per second, using the complete enumeration algorithm. It would take this machine 2 days to find an optimal schedule for a 20 parts problem and 400 centuries for 25 parts problem! Hence, other more constructive approaches, which do not search through the entire set, are the basis of most TSP algorithms.

HISTORICAL BACKGROUND

The MSP (TSP) and its solution procedures have continued to provide useful test grounds for many combinatorial optimization approaches. Classical local optimization techniques (see Rossman, 1958; Applegate et al., 1999; Riera-Ledesma, 2005; Walshaw, 2002; Walshaw 2001) as well as many of the more recent variants on local optimization, such as simulated annealing (Tian and Yang, 1993), tabu search (Kolohan and Liang, 2000), neural networks (Potvin, 1996) and genetic algorithms have all been applied to this problem, which for decades has continued to attract the interests of researchers. This section is a brief historical background of the TSP.

Although a problem statement posed by Karl Menger on February 5, 1930, at a mathematical colloquium in Vienna, is regarded as a precursor of the TSP, it was Hassle Whitney, in 1934, who posed the traveling salesman problem in a seminar at Princeton University (Flood, 1956).

A 1949 work, (Robinson, 1949), with an algorithm for solving a variant of the assignment problem is one of the earliest references that use the term "traveling salesman problem" in the context of mathematical optimization. However, a breakthrough in solution methods for the TSP came in 1954, when Dantzig et al. (1954) applied the simplex method (designed by George Dantzig in 1947) to an instance with 49 cities by solving the TSP with linear programming.

There were several recorded contributions to the TSP in 1955. Heller (1955) discussed linear systems for the TSP polytope, and some neighbor relations for the asymmetric TSP polytope. Also Kuhn, (1955) announced a complete description of the 5-city asymmetric TSP polytope. Morton and Land (1955) presented a linear programming approach to the TSP, alongside the capacitated vehicle routing problem. Furthermore, Robacker (1955) reported manual computational tests of some 9 cities instances using the Dantzig-Fulkerson-Johnson method, with average computational times of about 3 hours. This time became the benchmark for the next few years of computational work on the TSP.

In 1956, M.M. Flood discussed some heuristic methods for obtaining good tours, including the nearest-neighbor algorithm and 2-opt (Flood, 1956) while Kruskal, (1956) drew attention to the similarity between the TSP and the minimum-length spanning trees problem. The year 1957 was a quiet one with a contribution from Barachet describing an enumeration scheme for computing near-optimal tours (Barachet, 1957).

The year 1958 witnessed several contributions to the TSP archives. Croes (1958) proposed a variant of 3-opt together with an enumeration scheme for computing an optimal tour. He solved the Dantzig-Fulkerson-Johnson 49-city example in 70 hours by hand. He also solved several of the Robacker examples in an average time of 25 minutes per example. A similar contribution (Bock, 1958) describes a 3-opt algorithm together with an enumeration scheme for computing an optimal tour. The author tested his algorithm on some 10-city instance using an IBM 650 computer.

By 1958, work related to the TSP had become serious research to attract Ph.D. students. A notable work was a Ph.D. thesis (Eastman, 1958) where a branch-and-bound algorithm using the assignment problem to obtain lower bounds was described. The algorithm was tested on examples having up to 10 cities. Also that same year, Rossman and Twery (1958) solved a 13-city instance using an implicit enumeration while a step-by-step application of the Dantzig-Fulkerson-Johnson algorithm was also given for Barachet's 10-city example. There were at least five publications on the TSP in 1960. Bellman (1960) showed the TSP as a combinatorial problem that can be solved via dynamic programming.

In Miller et al. (1960), an integer programming formulation of the TSP and its computational results of solving several small problems using Gomory's cutting-plane algorithm was reported. Lambert (1960) solved a 5-city example of the TSP using Gomory cutting planes. Dacey, (1960) reported a heuristic, whose solutions were on average 4.8 percent longer than the optimal solutions.

TSP in 1960 achieved national prominence in the United States of America when Procter & Gamble used it as the basis of a promotional context. Prizes up to $10,000.00 were offered for identifying the most correct links in a particular 33-city problem. A TSP researcher, Gerald Thompson of Carnegie Mellon University won the prize (Applegate et al 2007).

In 1961, Müuller–Merbach proposed an algorithm for the asymmetric TSP; he illustrated it on a 7-city example. Ackoff et al. (1961) gave a good survey of the computational work on the TSP that was carried out in the 1950's.

By 1962, when the computer was becoming a useful tool in exploring the TSP, the dynamic programming approach gained attention. Gonzales solved instances with up to 10 cities using dynamic programming on an IBM 1620 computer (Gonzales, 1962). Similarly, Held and Karp (1962) described a dynamic programming algorithm for solving small instances and for finding approximate solutions to larger instances.

Using an IBM 7090 computer their exact algorithm solved 13-city instances while the approximation algorithm found the optimal solution to the 42-city Dantzig-Fulkerson-Johnson example on two out of five trials, and was also tested on a new 48-city instance.

Little et al. (1963) coined the term branch-and-bound. Their algorithm was implemented on an IBM 7090 computer and they gave some interesting computational tests including the solution of a 25-city problem that was in the Held and Karp test set. Their most cited success is the solution of a set of 30-city asymmetric TSPs (or MSP) having random edge lengths. In an important paper (Lin, 1965); a heuristic method for the TSP was published. The author defined *k*-optimal tours, and gave an efficient way to implement 3-opt, extending the work of Croes (1958) with computational results given for instances with up to 105 cities.

The year 1966 was another fruitful one for the TSP in terms of published works. Roberts and Flores (1966) described an enumerative heuristic and obtained a tour for Karg and Thompson's 57-city example, having cost equal to the best tour found by Karg and Thompson. Also, in a D.Sc. thesis at Washington University, St. Louis, Shapiro (1966) describes an algorithm similar to Eastman's branch-and-bound algorithm.

Gomory (1966) gave a very nice description of the methods contained in Dantzig et al. (1954), Held and Karp (1962), and Little et al. (1963). Similarly, in Lawler and Wood (1966) descriptions of the branch-and-bound algorithms of Eastman (1952) and Little et al. (1963) were given. The authors suggested the use of minimum spanning trees as a lower bound in a branch-and-bound algorithm for the TSP.

Bellmore and Nemhauser (1968) presented an extensive survey of algorithms for the TSP. They suggested dynamic programming for TSP problems with 13 cities or less, Shapiro's branch-and-bound algorithm for larger problems up to about 70-100 and Shen Lin's `3-opt' algorithm for problems that cannot be handled by Shapiro's algorithm. Raymond (1969) is an extension to Karg and Thompson's (1964) heuristic for the TSP where computational results were reported for instances having up to 57 cities.

Held and Karp in their 1970 paper introduced the 1-tree relaxation of the TSP and the idea of using node weights to improve the bound given by the optimal 1-tree. Their computational results were easily the best reported up to that time. Another notable work on the TSP in the 70s is the S. Hong, Ph.D. Thesis, at The Johns Hopkins University in 1972 written under the supervision of M. Bellmore, and the work was the most significant computational contribution to the linear programming approach to the TSP since the original paper of Dantzig et al. (1959). The Hong's algorithm (Hong, 1972) had most of the ingredients of the current generation of linear-programming based algorithms for the TSP. He used a dual LP algorithm for solving the linear-programming relaxations; he also used the Ford-Fulkerson max-flow algorithm to find violated subtour inequalities.

The algorithm of Held and Karp (1971) was the basis of some major publications in 1974. In one case, Hansen and Krarup (1974) tested their version of Held-Karp (1971) on the 57-city instance of Karg and Thompson (1964) and a set of instances having random edge lengths. In 1976 a linear programming package written by Land and Powell was used to implement a branch-and-cut algorithm using subtour inequalities. Computational results for the 42-city instance of Dantzig et al (1959), the 48-city instance of Held and Karp (1962) and the 57-city instance of Karg and Thompson (1964) were given.

Smith and Thompson, (1977) presented some improvements to the Held-Karp algorithm tested their methods on examples which included the 57-city instance of Karg and Thompson (1964) and a set of ten 60-city random Eucliean instances. In 1979, Land described a cutting-plane algorithm for the TSP. The decade ended with a survey on algorithms for the TSP and the asymmetric TSP (Buckard, 1979).

A very impressive work heralded the 1980s. Crowder and Padberg (1980) gave the solution of a 318-city instance described in Lin and Kernighan (1973). This 318-city instance would remain until 1987 as the largest TSP solved. This work improved on the earlier cutting-plane algorithm in Padberg and Hong (1980). Also, in 1980, Grötschel gave the solution of a 120-city instance by means of a cutting-plane algorithm, where subtour inequalities were detected and added by hand to the linear programming relaxation.

In 1982, Volgenant and Jonker described a variation of the Held-Karp algorithm, together with computational results for a number of small instances. A very important work of 1985 is a book (Lawler et al., 1985) containing several articles on different aspects of the TSP as an optimization problem. Padberg and Rinaldi (1987) solved a 532-city problem using the so-called branch and cut method.

The works in the 1990's were mostly application in nature. A large number of scientific/engineering problems and applications such as vehicle routing, parts manufacturing and assembly, electronic board manufacturing, space exploration, oil exploration, and production job scheduling, etc. have been modeled as the MSP or some variant of the TSP (see Al-Haboub-Mohamad and Selim, 1993; Clarker and Ryan, 1989; Crama et al., 2002; Ferreir, 1995; Foulds and Hamacher, 1993; G¨unther et al., 1998; Keuthen, 2003; Kolohan and Liang, 2000; Mitrovic-Minic and Krishnamurti 2006).

FUTURE DIRECTIONS

The re-examination and the development of further theoretical basis for these solution approaches have been identified as one way to develop more efficient and effective solution algorithms for the MSP (Charles–Owaba, 2001; Charles–Owaba 2002; Walshaw, 2002).

Recently, a Set Sequencing Algorithm was proposed as a basis for the MSP solution approaches. In the Set Sequencing paradigm (Charles–Owaba, 2001; Charles–Owaba, 2002) a complete tour is viewed as comprising a set of N TSP matrix elements (links). Set Sequencing is defined as the transformation of a known sequence (S_{i-1}) to a new sequence (Si) by feasibly replacing a subset of its links (Lr) with equal number (M) of candidate links (Lc) using a recursive function:

$$Va(S_i) = Va(S_{i-1}) + \Delta(Lr, Lc, M)$$

where $Va(S_i)$ and $Va(S_{i-1})$ are the respective sequence values and $\Delta(Lr, Lc, M)$ is the exact amount $Va(S_i)$ is changed by the replacement operation.

Consequently, an alternative TSP (MSP) model, Minimize $\Delta(Lr, Lc, M)$, has been defined and shown to be equivalent to the traditional MSP model, Minimize $Va(S_i)$.

It has also been established that just as an optimal sequence S* exits from among [N!] sequences, an optimal set L_c* also exits from among [N(N-1)] MSP matrix elements. A systematic procedure, the set sequencing procedure SSP, for scanning for Lc* was also developed (Charles–Owaba, 2001). In other words, an optimal solution (tour) of the N-station cyclic Asymmetric Traveling Salesman problem (or the Cyclic MSP) was viewed as consisting of (N) elements (optimal elements) of the distance matrix. Considering lower bound for elements a theoretical basis for identifying and eliminating non-optimal elements was suggested. This concept of element elimination was then used to define optimality conditions.

The approach for handling the subtours elimination constraints of the TSP integer LP is another area for re-examination. Researchers have identified the issue of feasibility or subtour elimination as very crucial in the formulation of the TSP or similar permutation sequence problem. "No one has any difficulty understanding subtours, but constraints to prevent them are less obvious," says Radin L.R in (Radin, 1998). Methodologies or theoretical basis for handling these constraints within the context of algorithm development has been the basis of many popular works on the TSP. A classical example of this approach is in Crowder and Paderg (1980) where a linear programming relaxation was adopted such that if the integral solution found by this search is not a tour, then the subtour inequalities violated by the solution are added to the relaxation and resolved.

Grötschel (1980) used a cutting-plane algorithm, where cuts involving subtour inequalities were detected and added by hand to the linear programming relaxation. Hong (1972) used a dual LP algorithm for solving the linear-programming relaxations, the Ford-Fulkerson max-flow algorithm, for finding violated subtour inequalities and a branch-and-bound scheme, which includes the addition of subtour inequalities at the nodes of the branch-and-bound tree. Such algorithms are now known as "branch-and-cut". The problem of dealing with subtour occurrences algorithm development has been a major one in the in the MSP studies in the literature.

For example, Oladokun (2006) adopted a schematic and graphical framework to characterize and explain the changes taking place during the transformation of an input sequence into a new sequence, a transition process was defined and characterised for the purpose identifying feasible links on the problems matrix. This approach was integrated into the SSA to yield a new solution algorithm called the subtour-free SSA.

MULTI CRITERIA SCHEDULING

One of the computational characteristics of iterative algorithms-such the SSA, Lin-Kernighan and the k-opt worth noting is that they generates many high quality sequences or schedules during the iteration process. Presently this intermediate information appears wasted. One area where this observation will be useful is when dealing with bi-criteria or multi-objective scheduling problems. In such cases these iterative algorithms may be part of an integrated solution procedure to generate high quality input sequences to be used as test solutions on the various criteria. In our view we suggest that the TSP research be approached from this more practical multi-objective scheduling perspective.

COMPOSITE ALGORITHMS AND PARALLEL COMPUTING

The performance of a TSP algorithm may be improved by combining it with some other procedure. For example in (Walshaw, 2001) the multilevel paradigm was applied to the TSP, in this attempt the Lin-Kernighan (Lin and Kernighan, 1973) algorithm was used as a refining procedure required after the multilevel coarsening process with the resulting combined procedure producing improved solutions (Walshaw, 2001; Walshaw, 2002). We are of the view that the concept of composite algorithms is another area that holds some attraction and is will continue to yield good results.

The adaptation of some of the existing algorithms for parallel computing over networked systems of personal computers have been shown to greatly expand the scope and capability of such algorithms (Applegate 2004, Oladokun 2006). This approach, we believe, should form the basis of further researches.

CONCLUSIONS

A brief overview of the well known Sequence Dependent Machine Setup Problem also called the Traveling Salesman Problem has been presented in this paper. The Problem has a wide range of applications and this has sustained continued interest on this NP hard problem. This problem will continue to stimulate interests due to its practical values in scheduling and theoretical relevance in discrete optimization studies.

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