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A disjunctive graph model and framework for constructing new train schedules

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ABSTRACT

Train scheduling is a complex and time consuming task of vital importance in many countries. To create completely new train schedules that are more accurate and efficient than permitted by current techniques, a novel "hybrid" job shop approach is proposed and implemented in this paper. Unique characteristics of train scheduling are firstly incorporated into a disjunctive graph representation of the solution. Dedicated "stand-alone" constructive algorithms that utilise this representation are then developed. The modelling approach and the constructive algorithms are essential as they provide the basis for which meta-heuristics and other iterative refinement algorithms can be applied. A numerical investigation and case study is provided and demonstrates the viability of the modelling approach. Furthermore it is demonstrated that good quality solutions are provided with reasonable computational effort.

1. Introduction

Trains provide a relatively clean and cheap method of transportation for passengers and freight, and compare favourably if not better than alternative modes of transportation such as road, air and sea in many circumstances. Furthermore the utilisation of railway systems can only increase in the future as roads become even more congested, trains become faster and infrastructure is extended. Due to the size, weight and speed of trains the coordination of train movements (by train scheduling) is vital in order to utilise these systems safely and effectively. However train scheduling on current systems is still a relatively difficult and time consuming task as the size and complexity is prohibitive. Train scheduling problems have unique properties and pose a number of unique difficulties that distinguish it from other related scheduling problems. These will be discussed in a later section. The manual construction of a schedule by a human expert with the help of computer software is the most common first and last resort in practice.

In practice there are a variety of different scheduling problems that must be solved, though in principle two main variants exist. The first considers the development of a new timetable that is typically but not necessarily to be applied at regular intervals such as daily, weekly or monthly. The second scheduling problem concerns the re-development of an existing timetable. For example, an existing timetable may become undesirable and or infeasible after unforseen delays have caused significant deviations to the original plan. In the first variant there is usually no limitation on when trains may enter the system, i.e. they may enter at any time. However in the second variant trains have to enter at predefined time and some trains may already be within the system at the start of the schedule.

In recent years the majority of papers in the literature have addressed the second "rescheduling" problem, and examples include Carey (1994a,b) and Higgins et al. (1996) for exact approaches and Cai and Goh (1994), Higgins et al. (1997), Cai et al. (1998), Chiang et al. (1998), Sahin (1999), Adenso-Diaz et al. (1999), and Dorfman and Medanic (2004) for heuristic approaches . The first problem has been addressed more recently by Odijk (1996), Brannlund et al. (1998), Goverde (1999), Lindner (2000), Kroon and Peeters (2003), Ghoseiri et al. (2004) and Zhou and Zhong (2005). Train platforming and pathing is another aspect that has received attention recently by Carey and Lockwood (1992), Romeijn et al. (1996), Zwaneveld et al. (1996), Kroon et al. (1997), Cordeau et al. (1998), Zwaneveld et al. (2001), Billionnet (2003), Carey and Carville (2003).

In this paper the development of completely new train schedules via a new "hybrid" job shop scheduling approach is considered. More specifically this paper considers the most efficient way for a specified number (mix) of trains with predefined routes to traverse a railway system (network) between their predefined origin and destination location subject to a variety of technical constraints. A railway system is a single track or a complex network of interconnected tracks. A makespan objective criterion is used in this paper to measure the relative merits of a new timetable though other criterions could easily be used as our approaches are quite independent. The makespan objective is a well known scheduling measure and provides a good benchmark for comparing the efficiency of the techniques proposed in this paper. In our experience train scheduling criteria varies from one region and operator to the next and when constructing a new timetable the best

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objective criterion is particularly debatable. What is clear though is that new schedules are not affected by previous "timings". Therefore minimising delays such as those caused by the non-adherence to an existing schedule is not applicable. Furthermore minimising scheduled delays is not entirely sufficient because trains may be scheduled with no delays but the schedule horizon (makespan) can be very large. In other words throughput will be very poor and this is not particularly desirable. New timetables should be efficient in terms of throughput at least in certain time periods and the makespan objective is good for achieving this. The makespan minimisation criterion is also particularly useful as it allows the capacity of the system for a specific mix of trains to be accurately determined. No other fool proof method exists to our knowledge. In this scenario timetable creation may be viewed as a tool for making higher level economic decisions. For more information on capacity determination approaches and theory (Burdett and Kozan, 2006; Kozan and Burdett, 2005) may be consulted.

In the next section the theory behind the application of a job shop scheduling approach is presented. In Section 3 unique characteristics of train scheduling are firstly incorporated into the disjunctive graph representation of the solution. Constructive algorithms that utilise this representation are then developed in Section 4. A numerical investigation and case study then demonstrates in Section 5 the suitability of the proposed approaches and the quality of solution that can be obtained. In the last section the outcomes and the significance of the paper is summarised and the future research directions are given.

2. The job shop approach

To our knowledge a schedule is currently constructed manually or heuristically by manipulating the schedule representation of the solution. The schedule representation is either a list of train arrival/departure times from specific locations that it passes or a list of entry/exit times from each section that it traverses. A sequence based representation of the problem however is also possible. For example a schedule may be represented as a unique sequence of train movements on each section of the railway. When this representation is used the problem is analogous but not synonymous to the job shop problem. The job shop problem (JSP) in particular is concerned with the scheduling of jobs on machine resources.

There are a number of benefits that in theory could be attained by treating the train scheduling problem as a "hybrid" job shop problem and a list of ***some*** of these are as follows:

- Previous approaches have typically only addressed one train scheduling variant or another. A hybrid job shop approach (i.e. framework and solution strategies) is very generic, all encompassing and in theory is suitable (with perhaps some modification and extension) for any or all of the variant train scheduling problems.
- Conventional train scheduling often uses discrete time units. This reduces the accuracy a little and requires some assumptions about rounding. Equally as many approaches use continuous time variables but rounding complications still exist. That is, the minimum recognisable time unit must be defined. Job shop scheduling techniques operate on the "discrete" sequence representation of the solution. Therefore the direct manipulation of continuous or integer based scheduling variables which causes rounding difficulties and inaccuracies is unnecessary.
- The sequence representation does not allow two trains to intersect or otherwise cross on any section because there is a unique sequence of separate train movements. Hence conflict identification and resolution procedures which are currently used and require considerable amounts of computation time are no longer required if the sequences are upheld.
- Trains may be scheduled on any complex non-serial railway network. There is no additional complexity in the job shop approach.
- Return paths and circular paths which require a job to occupy a machine more than once is more easily incorporated.
- Removing a train from a schedule leaves all other trains untouched in the conventional representation and solution approach. In the job shop approach all following trains are rescheduled automatically via the disjunctive graph. They are then scheduled as early as possible. Cycles in the graph are not created by removing trains from a currently feasible schedule.

The job shop problem may be solved in a variety of different ways, however due to the intractable nature of the problem inexact iterative procedures and algorithms are more commonly used. Inexact methods for solving the JSP are usually based upon a directed graph representation of the solution. For the standard JSP, nodes and arcs respectively represent operations and the precedence's between operations. Arcs are defined as either conjunctive or disjunctive and have a weight of zero. In particular disjunctive arcs represent precedence's between operations of different jobs while conjunctive arcs represent precedence's between operations of the same job. Nodes weights are equal to the operation processing time. A source node and a sink node are also added to the graph. The first and last operation of each job is attached from the source and to the sink node respectively. The longest path from the source to the sink node defines the schedule and gives the makespan. A new schedule may be obtained for example by selecting and reversing "critical" disjunctive arcs. Reversing a disjunctive arc is equivalent to reversing the position of two jobs within a machine sequence.

In this paper the latter job shop approach is taken as it is new and more importantly because it has the potential to be significantly better than other existing approaches. To our knowledge the strategies taken in this paper have not been taken before for train scheduling. In recent years however some aspects of the train scheduling problem have been addressed separately in the machine scheduling literature. These include: Werner and Winkler (1995), Dauzere-Peres and Paulli (1997), Nowicki (1999), Mastrolilli and Gambardella (2000), Mati et al. (2001), Mascis and Pacciarelli (2002), Kis (2003), Corry and Kozan (2004), Murovec and Suhel (2004) and Zoghby et al. (2005). In summary these papers have addressed scheduling problems with routing flexibility, capacitated buffers, blocking conditions, sequence dependant setup times, parallel machines, and more complex technical constraints. A more in-depth review of this literature is as follows:

Werner and Winkler (1995) motivated by the good results of insertion algorithms for a number of combinatorial optimisation problems developed insertion algorithms and iterative improvement algorithms for the heuristic solution of job shop problems. It was reported that the developed constructive algorithm yielded better results than the majority of the usual priority dispatching rules for generating an active schedule. The constructive algorithms of this paper are based upon similar logics used in the algorithms of Werner and Winkler.

Dauzere-Peres and Paulli (1997) considered an important generalisation of the classical job shop scheduling problem where operations can be performed on alternative machines. The problem is to assign each operation to a machine and to sequence the operations on each machine. An extended disjunctive graph model was presented. A neighbourhood structure was created that merges the reassignment and re-sequencing of an operation. A tabu search approach that utilises this neighbourhood was developed and was shown to be superior to prior heuristics for this problem. This work is particularly applicable for train scheduling because crossing loops are a situation where an operation can be processed on alternative machines. In this paper the refinement of a schedule is not concentrated upon as it is in the paper of Dauzere-Peres and Paulli.