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A MAS architecture for dynamic, realtime rescheduling and learning applied to railway transportation

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ABSTRACT

Rescheduling disrupted railway traffic is computationally hard even for small problem instances. Disruptions may not be known beforehand and can manifest themselves even when trains are en-route, and they are usually resolved by human experts. Wide geographical distribution, a dynamically changing environment, complex interdependencies between multiple components, operational criticality and uncertainty being characteristic of railway transportation, human resolutions are inconsistent, scale-inefficient and potentially infeasible with deadlocks. We present a multi-agent system (MAS) model for dynamic and real-time rescheduling (DRR) of bi-directional railway traffic on a single track in this paper. A computational framework to dynamically dispatch the disrupted trains in real-time, based on instantaneous system parameters and to reschedule conflicting trains with inherent deadlock avoidance is incorporated in the agents' model. A learning architecture is implemented as a proof-of concept to resolve disruptions quickly and to enhance autonomy. The model is evaluated against integer optimal solutions generated by a Mixed-Integer Linear Programming (MILP) model using realistic data. Detailed discussions on architecture, implementation using JADE (Java Agent DEvelopment) toolkit, experimental results, performance analysis, evaluation of the model, insights and limitations are reported. The numerical performance measures of the model are total weighted delay of all trains at their destination terminals and computational time for resolution. The distinguishing research contributions in this paper are a MAS architecture for railway rescheduling, dynamic dispatch priority assignment using bidding and a learning procedure that enhances autonomy.

1. Introduction

Railway transportation services are planned meticulously and are often published in a timetable well in advance as a commitment of public service. A timetable tabulates arrival, departure times of trains and train orders at each halt location and is conflict-free. If a disruption occurs within the time and spatial domain of such a feasible schedule, it leads to service delay and at times to a conflict; conflict is a safety constraint violation, at which two or more trains demand to occupy a track segment simultaneously. Hence both train schedules and sequencing, which is the arrival and departure ordering at stations need to be modified. In heavy rail transportation, human dispatchers resequence and reschedule disrupted traffic. Disruptions are resolved using two different approaches – a planned maintenance approach (prior to actual disruption occurrence), where schedules are modified earlier to disruption occurrence and at stations located before the actual disruption location or a rescheduling approach (as and when disruptions occur), where schedules are modified from the disruption location and instant of occurrence. Human dispatchers adopt a thumb rule approach to reschedule, and there are inherent drawbacks in their solutions. One is that they follow standard sequencing procedures such as FCFS, Maximum tardiness first, Early arrival at destination first etc., which is not effective in resolving all types of disruptions. Second, it is near impossible for human dispatchers to predict if a current resolution will lead to future delay and additional conflicts in the operational domain. In this paper, a multi-agent system model to reschedule disrupted railway traffic is presented. The motivation behind our approach is to overcome some of the limitations of a human dispatcher's thumb rule based resolutions. Dynamic decision making and real-time resolutions are two significant features of the multi-agents system presented in this paper and brief discussions are given below.

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Dynamic decision making: Dispatch decisions do not follow the standard sequencing procedures; rather dispatch priority is decided on a case-to-case basis, as and when disruptions occur.

- A minor incident can cause either safety violations or a quality loss in objective and can make a planned feasible schedule ineffectual. Corman, D'Ariano, Pacciarelli, and Pranzo (2012a) report that human experts detect, resolve disruptions and restore the schedule, by deciding dispatch orders. Human decisions lack analysis of future impacts, consistency and accountability. Such dispatch decisions are likely to create deadlocks, when two or more trains demand track segments, mutually occupied by each other.
- Effective computation is essential to prevent deadlocks and to maintain feasibility, consistency and convergence of disruption resolutions.
- Deriving a feasible, conflict free reschedule and optimizing some performance objectives are most effective (Kraay & Harker, 1995) when schedule parameters that vary dynamically under a disruption are quantitatively applied in dispatch orders.
- Modeling parameters of failure and consequences of failure in dispatch decisions minimizes deviations in schedule objectives according to Sahin (1999).

Real time resolution: Resolutions must be quick enough for rescheduling to be effective in real-life situations, even for large problem sizes. Computational time should be minimized, by utilizing all available resources.

- Computations must be fast in generating solutions so that disruptions are resolved in realistic time.
- Railway rescheduling in practice is a large sized problem that demands huge computational resources. Resources that are diverse and dispersed can be utilized in a coordinated manner, if they are portable and inter-operable. Portability means that the applications allow execution on different platforms or operating systems. Inter-operability refers to the support and ease of data and applications transfer between diverse computational resources.
- Constant human intervention is detrimental to real-time applications. Resolution methods need to self-invoke.
- Railway scheduling rules are enforced strategically, though case-to-case modifications are sometimes necessitated. An extensible computational technique allows modifying the underlying constraints set and the scheduling logic with ease.
- Future expansions in railway services demand an increase in the size of problem and data. Computational methods are more scale effective than human dispatchers so that performance quality is not affected by increase in problem size.

Railway operational plans get disrupted quite often and it is essential to restore the services. The problem is addressed both in existing research and practise. Most of the existing literature consider the problem as a planned maintenance, in a way to prevent disruptions and conflicts, which does not reflect rescheduling challenges in reality. Human dispatchers reschedule disrupted trains in practice; solutions of which are difficult to validate and verify. The major significance of our approach is that it is an attempt to fill both the gaps. Restoration of disrupted traffic, as and when disruption occurs is the objective of the proposed model; Multi-agents systems in railway rescheduling generate valid computational solutions that are evaluated against other comparable techniques.

The rest of the paper is organized as follows. Literature related to railway rescheduling approaches and agents based solutions are discussed in the following Section 2. This section is summarized with lacuna in existing contributions. In Section 3, the dynamic and realtime railway rescheduling problem is introduced with premises under which the resolution is proposed. Succinct definitions of generic terms, notation, specific to our model and an illustrative scope of the problem we address are also presented. We present our agents based solution as a conceptual illustration in Section 4. We summarize this section with how our model offsets limitations in current research and contributes to a novel dispatch procedure. The entire rescheduling procedure is described in detail in Section 5. Learning is a new attempt in this area of research and we have developed a learning agents based proof-of concept to enhance certain performance criteria. Our learning architecture is described in Section 6. Note-worthy features are mentioned briefly in both the above sections. Details of experimentation are presented in Section 7, followed by numerical results, analysis and evaluation against another comparable dispatch procedure in Section 8. Section 9 lists our experiential inferences and insights from this research work. We conclude the paper with our specific contributions, limitations of work and possibilities of future extensions in Section 10.

2. Literature review

We discuss some published research in the areas of railway transportation and literature that address rescheduling using OR and distributed systems. Carey et al. (1995) proposed one of the earliest models for train pathing on a single track railway. They developed a Mixed Integer Programming (MIP) model to minimize cost associated with train arrivals and departures. A heuristic solution was proposed to path a new service on a single track network with the objective of minimizing arrival/departure costs and to preserve the arrival/departure orders of the scheduled trains. This approach can be adapted to reschedule disrupted services, when disrupted trains can be re-instated into the existing timetable as new services. Cai and Goh (1994) developed a MIP model for scheduling trains on a single track. Higgins, Kozan, and Ferreira (1996) proposed a mathematical model as a decision support tool to optimally dispatch trains in real time and as a planning tool to evaluate impacts of changes in timetable and infrastructure. Kraay and Harker (1995) presented an optimal model to schedule freights in real time and link the model with strategic solutions. Walker, Snowdon, and Ryan (2005) proposed a new model for the combined scheduling of trains and crew, and extended it to a disruption recovery model. Another rescheduling objective is to maximize utilization by increasing the number of passengers using a train service, proposed by Diaz, Gonzalez, and Gonzalez-Torre (1999). Sahin (1999) proposed a total delay minimization objective to resolve inter-train conflicts arising out of disturbance. Disturbance locations and time instants are specified and trains that conflict are identified. A dispatch precedence is decided using a proposed ranking heuristic among two immediately conflicting trains detected one after the other. Sahin (1999) subsumed that the number of future conflicts and the total future delay are key determinants to delay minimization. Cheng (1996) proposed a simulation based optimal traffic rescheduling by identifying the critical and non-critical paths in a schedule. Cheng (1998) developed a hybrid – network based and event driven simulation to resolve train conflicts. This approach is observed to be more efficient in dynamic environments. Perturbations in a single track schedule are handled as a discrete event based simulation and a local feedback based travel advance strategy by Dorfman and Medanic (2004). Other approximate conflict resolutions in railway applications are towards constraint propagation (Chiu, Chou, Lee,