Ant Colony Optimization for Energy-Efficient Train Operations

Federico Naldini
DEI, Alma Mater Studiorum, University of Bologna
Bologna, Italy
federico.naldini4@unibo.it

Paola Pellegrini
COSYS-LEOST, Univ Gustave Eiffel, IFSTTAR, UnivLille
Villeneuve d'Ascq, France
paola.pellegrini@univ-eiffel.fr

Joaquin Rodriguez
COSYS-ESTAS, Univ Gustave Eiffel, IFSTTAR, UnivLille
Villeneuve d'Ascq, France
joaquin.rodriguez@univ-eiffel.fr

ABSTRACT

Traffic perturbations in railway systems may give rise to conflicts, which cause delays w.r.t. the timetable. Dealing with them requires solving the real-time Rail Traffic Management Problem (rtRTMP). A subproblem of the rtRTMP is the real-time Energy Consumption Minimization Problem (rtECMP). It defines the speed profiles along with the timing of multiple trains in a given network and time horizon. It takes as input the train routing and precedences computed by a rtRTMP solver and its objective is to minimize the weighted sum of train energy consumption and total delay. In this paper, we propose an Ant Colony Optimization algorithm for the rtECMP and we test it on the French Pierrefitte-Gonesse control area with dense mixed traffic. The results show that, in 30 seconds, a remarkable exploration of the search space is performed before convergence.

CCS CONCEPTS

• **Applied computing** → **Transportation**; • **Computing methodologies** → **Multi-agent systems**;

KEYWORDS

Energy consumption, Multiple trains, Ant Colony Optimization, Traffic Management

ACM Reference Format:

Federico Naldini, Paola Pellegrini, and Joaquin Rodriguez. 2021. Ant Colony Optimization for Energy-Efficient Train Operations. In *2021 Genetic and Evolutionary Computation Conference Companion (GECCO '21 Companion), July 10–14, 2021, Lille, France.* ACM, New York, NY, USA, 2 pages. https://doi.org/10.1145/3449726.3459436

1 INTRODUCTION

Railway systems are subject to unforeseen events causing traffic perturbations. They often give rise to *conflicts*, that occur when at least one train encounters a restrictive signal demanding an unplanned deceleration. Conflicts cause delays w.r.t. to the nominal timetable, that can propagate to the whole system in a snow-ball effect. The task of managing traffic to reduce delay is entrusted to a *dispatcher*, who is in charge of a *control area*. This is a limited size portion of the railway network. Dispatchers can decide upon train-route assignment (routing) and train ordering along common passing locations (scheduling), in addition to retiming trains at scheduled stops. These decisions have to be taken in a very short time frame, as soon as relevant conflicts are forecast. The problem faced by dispatchers is commonly referred to as *real-time Railway Traffic Management Problem* (rtRTMP) [4] and its solution is a feature of modern rail *traffic management systems* (TMS).

The *real-time Energy Consumption Minimization Problem* (rtECMP), as introduced by [2], has the objective of minimizing the weighted sum of train energy consumption and total delay by deciding the speed profiles in a given control area and time horizon. It takes as input the decisions on train routing and precedences made by a rtRTMP solver. In addition, to define energy-efficient speed profiles for multiple interacting trains, it takes into accounts infrastructure characteristics, operational constraints and train dynamics. The rtECMP ouputs include arrival, departure, passing through and dwelling times along with speed profiles. As the rtRTMP, given its real-time nature, the rtECMP has to be solved in a short computing time which starts when the TMS is called to address newly forecast perturbations. Under this computing time limit, we first need to solve a rtRTMP instance, then solve the corresponding rtECMP instance.

In this paper, we propose a graph-based rtECMP model that we explore with an Ant Colony Optimization (ACO) algorithm, which we name ACO-rtECMP. An experimental analysis is conducted on a real life railway infrastructure (Pierrefitte-Gonesse junction, located in France) subject to various traffic perturbations.

2 GRAPH-BASED APPROACH

We consider a microscopic representation of rail infrastructures. Specifically, the infrastructure in a control area is composed of *block sections*, which are track stretches that can be traversed by only one train at a time to maintain safe distancing. Every train is assigned a route in the infrastructure by a TMS. More precisely, we define a route as a sequence of block sections linking an origin-destination pair. Origins and destinations can either be at the limit with another, adjacent control area or a station platform. Stations can be inside the control area.

To ensure the coherence of route formation, control areas are equipped with an *interlocking system*. When a route is set, the signaling system indicates whether a block section can be accessed or not: every block sections is delimited by two signals placed at its entrance and exit location (see for instance [3]). In the simplest case, a signal is capable of displaying three different aspects: green, yellow and red. A red aspect forbids the access to the following block section. A signal displaying yellow allows the access and demands a slow down so that a full train stop is possible before the following signal. Green grants the access to a block section and

GECCO '21 Companion, July 10–14, 2021, Lille, France

ACM ISBN 978-1-4503-8351-6/21/07.
https://doi.org/10.1145/3449726.3459436

implies that a driver can safely enter the following one at full speed, if suitable.

Given a block section b, we refer to all block sections sharing at least one track-circuit with b as *incompatible*. Block section b is available for a train t only if all its incompatible block sections are free and none of them is to be used by another train before t.

We propose a graph model for the rtECMP in which we represent a speed profile as a concatenation of pre-computed partial speed profiles, one for each block section in a train's route. Given a train that has stopped in a block section, in the model the train restarts as soon as the following block in its route becomes available.

We are given a set of trains $i \in T$ and a route B_i for each of the trains. We refer to a generic block section in the route of train i as $j \in B_i$. For each $i \in T$ and $j \in B_i$, we are provided with train precedence in the form of a set $\mathcal{P}_{i,j}$ containing train-block pairs (i^*, j^*). Only when every train i^* has released its block j^*, i can access j. For each block section $j \in B_i$, we pre-compute a discrete set of partial speed profiles having the following attributes: an initial speed; a final speed; a value of energy consumed; a running time.

Let $G = (V, A)$ be a graph with V and A set of vertices and arcs respectively. Except for two special vertexes, *source* (s) and *terminal* (t) (which indicate the beginning and end of every path in the graph), each vertex represents a partial speed profile for a train-block pair. The attributes of a generic $v \in V$ are denoted by: i_v (train to which the vertex refers); j_v (the considered block section of B_{i_v}); k_v (initial speed); k'_v (final speed); r_v (running time of i_v in j_v); E_v (energy consumption).

The set of arcs A of graph G is defined as follows:

- For all $a, b \in V$ such that $i_a = i_b = i$, arc (a, b) exists if all following statements are true: j_a directly precedes j_b in train i's route; the final speed associated to node a is equal to the initial speed associated to node b, i.e., $k'_a = k_b$.
- For all $a, b \in V$ such that $i_a \neq i_b$, arc (a, b) exists if one of the following conditions is verified: (i_a, j_a) is in $\mathcal{P}_{i_b, j_b}$; j_a and j_b are compatible.
- For all $v \in V$, arc (s, v) exists if the train-block pairs (i_v, j_v) verifies the following conditions: j_v is the first block section in the route of i_v; no other train precedes i_v in j_v, i.e., $\mathcal{P}_{i_v, j_v} = \emptyset$.
- For all $v \in V$, arc (v, t) exists if j_v is the last block section of the route of train i_v.

A path h in G that satisfies a set of constraints represents a feasible solution of the problem. Precisely, h must satisfy the following constraints:

C1 [*Partial speed profile selection*]: For each $(i, j) : i \in T, j \in B_i$, exactly one vertex v such that $(i_v, j_v) = (i, j)$ must be in h. This ensures that a choice of a partial speed profile for a train-block pair is made and is unique.

C2 [*Speed profile continuity*]: For each $v, w \in h$ referring to two consecutive block sections j_v and j_w that have to be traversed by a train ($i_v = i_w$), it must be true that $k'_v = k_w$. This ensures speed profile continuity on the boundaries between every pair of consecutive block sections traversed by a train.

C3 [*Signaling*]: For each $v \in h$, k'_v must be coherent with the signal aspect opening block section j_v when i_v enters it. This constraint models the functioning of the signaling system.

To account for the two objectives of the rtECMP, i.e., energy efficiency and delay reduction, we minimize the weighted sum of two terms accounting for the normalized total energy consumption and delay. The corresponding weights are parameters of the algorithm.

3 ALGORITHM AND EXPERIMENTS

To tackle the graph model we proposed in this section, we use an ACO algorithm [1]. Precisely, we adopt a $\mathcal{MAX}$–$\mathcal{MIN}$ *ant system* ($\mathcal{MM}$AS) algorithm [5], to which we refer as *ACO-rtECMP*. Graph G is used as the construction graph in ACO-rtECMP.

We test ACO-rtECMP on 50 instances derived from the peak-hour traffic in the French Pierrefitte-Gonesse control area. For each instance, we study the improvement of the best ACO-rtECMP solution w.r.t. the best one found in the first iteration with a wall-clock time limit of 30 seconds (following [2]).

First, to display the non-trivial nature of this problem, we show how ACO-rtECMP results significantly outperform those of a random search conducted with the same settings. Second, we perform an experimental analysis that documents the impacts of shifting the optimization priority from energy consumption to delay reduction by varying the objective function weight configuration. By focusing on energy consumption minimization, the most remarkable improvements are obtained. This seems to be due to the range of the ACO heuristic information η becoming narrower as the weight of total delay minimization is increased, making η irrelevant to the search.

4 CONCLUSION & FUTURE RESEARCH

In this research, to address the rtECMP [2], we developed a graph model and $\mathcal{MM}$AS algorithm. We showed its applicability in realistic instances representing railway traffic in a French control area.

In future research, we will study whether a different definition of the ACO heuristic information may prevent the narrowing of its range and improve the algorithm performance. We will also extend ACO-rtECMP with a local-search algorithm, which is generally known to improve solution quality in conjunction with meta-heuristics as ACO. Future work will also be devoted to benchmarking the ACO-rtECMP results against an exact rtECMP solver, such as TDRC-MILP [2], on different infrastructures.

REFERENCES

[1] Marco Dorigo and Thomas Stützle. 2004. *Ant Colony Optimization*. The MIT Press.
[2] Teresa Montrone, Paola Pellegrini, and Paolo Nobili. 2018. Real-time energy consumption minimization in railway networks. *Transportation Research Part D: Transport and Environment* 65 (2018), 524 – 539. https://doi.org/10.1016/j.trd.2018.09.018
[3] J. Pachl. 2002. Spacing trains. *Railway Operation & Control* (2002), 38–90.
[4] Paola Pellegrini, Grégory Marlière, and Joaquin Rodriguez. 2014. Optimal train routing and scheduling for managing traffic perturbations in complex junctions. *Transportation Research Part B: Methodological* 59 (2014), 58 – 80. https://doi.org/10.1016/j.trb.2013.10.013
[5] Thomas Stützle and Holger H. Hoos. 2000. MAX–MIN Ant System. *Future Generation Computer Systems* 16, 8 (2000), 889 – 914. https://doi.org/10.1016/S0167-739X(00)00043-1