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Cuckoo search approach for automatic train regulation under capacity limitation

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Dear editor,

In the daily operation of metro systems, external interferences (e.g., signal system malfunction, bad weather) that can affect normal train operation are inevitable. Hence, effective train regulation measures are necessary to ensure service quality and efficient operation [1, 2]. With the explosive growth in the urban rail transit ridership in recent years, the manual train regulation has been unable to meet the requirements of the safety and effectiveness of metro operations because it is difficult for dispatchers to consider complex dynamic passenger flows while regulating trains [3]. Therefore, it is necessary to develop and improve automatic train regulation technology. With the advances in smart card technology, the history data of passenger flow obtained from the automatic fare collection system have been applied to analyze problems in metro train regulation/timetabling [3–6]. In these previous studies, the dynamic passenger flow was integrated into the train regulation model without considering the platform capacity. In other words, the platform capacity was assumed to be unlimited, which is not so in practice. The aim of this study is to investigate the real-time automatic train regulation problem considering the limited capacity of metro systems. The cuckoo search (CS) algorithm is adopted to solve the proposed model successfully.

Optimization model. The assumptions and relevant notations are provided in Appendix A. The stakeholders involved in the train regulation are operation companies and passengers. The operation company needs to reduce delays as much as possible to ensure a punctuality rate. On the other hand, passengers on the platform are unwilling to be left behind by a train that is about to depart. In the meantime, the number of stranded passengers on the platform increases with the delay time and the time interval between two consecutive trains, which needs to be controlled to eliminate potential safety hazards caused by overcrowding. Hence, the optimization model can be formulated as follows:

$$\min f = a_1 \cdot \frac{O_1}{O_1'} + a_2 \cdot \frac{O_2}{O_2'}, \tag{1}$$

$$O_1 = \sum_{i=1}^{|I|}\sum_{j=1}^{|J|} \left\{(x_{i,j} - A_{i,j}) + (y_{i,j} - D_{i,j})\right\}, \tag{2}$$

$$O_2 = \sum_{i=1}^{|I|}\sum_{j=1}^{|J|} l_{i,j}, \tag{3}$$

subject to

$$x_{s,t} = A_{s,t}, \tag{4}$$

$$y_{s,t} \geqslant D_{s,t} + d_{s,t}, \tag{5}$$

$$x_{i,j} \geqslant A_{i,j}, \tag{6}$$

$$y_{i,j} \geqslant D_{i,j}, \tag{7}$$

$$x_{i,j} - y_{i-1,j} \geqslant R^{\mathrm{l}}_{i-1,j}, \tag{8}$$

$$x_{i,j} - y_{i-1,j} \leqslant R^{\mathrm{u}}_{i-1,j}, \tag{9}$$

$$y_{i,j} - y_{i,j-1} \geqslant H_1, \tag{10}$$

$$x_{i,j} - x_{i,j-1} \geqslant H_1, \tag{11}$$

$$x_{i,j} - y_{i,j-1} \geqslant H_2, \tag{12}$$

$$y_{i,j} - x_{i,j} \leqslant W^{\mathrm{u}}_{i,j}, \tag{13}$$

$$y_{i,j} - x_{i,j} \geqslant W^{\mathrm{l}}_{i,j}, \tag{14}$$

$$W_{i,j} = a_0 + b_0 \cdot b_{i,j} + c_0 \cdot a_{i,j} + d_0 \cdot \left(\frac{w_{i,j}}{N}\right)^3 \cdot b_{i,j}, \tag{15}$$

$$W^{\mathrm{l}}_{i,j} = \max\{S^{\min}_{i,j}, W_{i,j}\}. \tag{16}$$

Eq. (1) implies that the objective is to minimize the total train delay O_1 and the number of stranded passengers on platform O_2, where a_1 and a_2 are positive weight factors; O_1' and O_2' are the normalization values of the total train delay and the number of passengers left behind on the platform, respectively. O_2 can be calculated by the passenger flow simulation model described in Appendix A. Constraints (4) and (5) denote a typical delay scenario in which a departure delay occurs on train t when it dwells at station s. Constraints (6) and (7) provide the lower and upper bounds for decision variables. Constraints (8) and (9) provide the lower and upper bounds for train running time. Constraints

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(10)–(12) indicate that the minimum headway between two successive trains should be satisfied to achieve safe operation. Constraints (13) and (14) provide the lower and upper bounds for train dwell time. For metro systems with high-volume passenger flow, the actual dwell time of a metro train is easily affected by the ridership. According to Puong [7], factors such as the number of boarding and alighting passengers and the level of crowding at the train door contribute to the metro train dwell time. This dwell time is as shown in (15), where a_0, b_0, c_0, and d_0 are dwell time coefficients. They can be obtained by the regression analysis. N is the number of opened train doors. The fourth term is the mean congestion degree at each train door. Constraint (16) defines the lower bound for the dwell time, where $S_{i,j}^{\min}$ is the default minimum dwell time. The minimum and maximum dwell time $W_{i,j}^{\mathrm{u}}$ are both predefined by the metro operator.

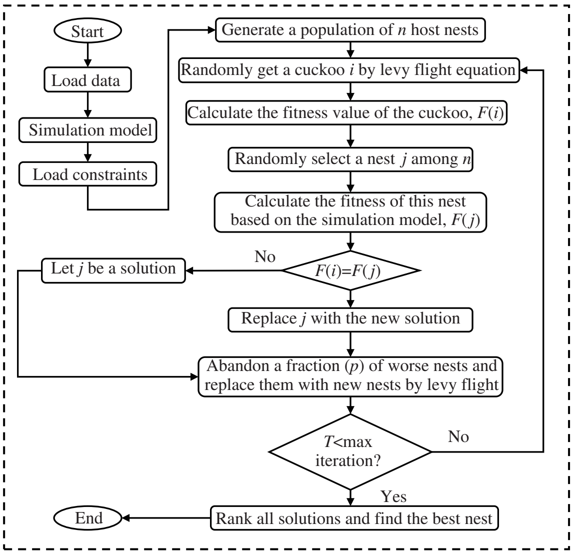

Figure 1 Flowchart of CS for the automatic train regulation problem.

Cuckoo search algorithm. CS is a novel metaheuristic algorithm proposed by Yang in 2009 [8]. In this algorithm, a group of nests is regarded as a population, and the eggs in each nest are regarded as a feasible solution to the optimization problem. We adopted the CS algorithm because of the following reasons: (1) Since the proposed model is nonlinear and commercial software cannot directly solve it, we focused on a metaheuristic algorithm. (2) Studies show that the CS algorithm performs better than many existing metaheuristic algorithms (e.g., GA and PSO) in standard tests. (3) This algorithm involves only a few parameters, and hence, it can be conveniently applied for optimization problems. The flow chart of the CS algorithm to solve the proposed model is shown in Figure 1. The position-update formula and the detailed procedure of the CS algorithm are described in Appendix B.

Case study. To demonstrate the proposed method, we conducted three experiments based on the operation data of Beijing Subway Line 9. First, we conducted parameter-tuning experiments to identify a set of appropriate parameters for the CS algorithm. Then, a typical delay scenario was used to validate the effectiveness of the proposed method. Second, the weight coefficients for the total train delay and the total number of stranded passengers on platforms were investigated. Finally, we designed several scenarios with different disturbance locations and initial delay durations to validate the reliability of the proposed method for solving the automatic train regulation problem. The parameter settings and detailed discussion of experiments are provided in Appendix C.

Conclusion. In this study, we developed an automatic train regulation model that considers the limited capacity of trains and platforms. We solved the proposed model by using the CS algorithm and conducted three case studies based on the real operation data of Beijing Subway Line 9. The computation results indicate that by choosing an appropriate parameter set for the algorithm and weight set for the objectives, the proposed method can effectively solve the automatic train regulation problem. In future research, we will consider further reducing the number of stranded passengers by adopting train holding and skip-stop strategies, in which the additional waiting time of in-vehicle passengers and the passengers left behind will be studied. Furthermore, the passenger flow control strategy will be integrated into the train regulation model, and the impact of different weights on the objective function for passengers waiting at the platform and waiting outside the station will be examined.

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Supporting information Appendixes A–C. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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