The unit train make-up scheme for loaded direction in the heavy haul railway

Yuqiang Wang and Yuguang Wei
Beijing Jiaotong University, Beijing, China

Hua Shi
Arizona State University, Tempe, Arizona, USA

Xinyu Liu
China Railway Economic and Planning Institute, Beijing, China

Liyuan Feng
China Railway Siyuan Survey And Design Group Co. Ltd., Wuhan, China, and

Pan Shang
Beijing Jiaotong University, Beijing, China

Abstract

Purpose – The purpose of this paper is to study the unit train make-up scheme for loaded direction in the heavy haul railway.

Design/methodology/approach – A 0-1 nonlinear integer programming model with the aim of minimizing the idling period between actual train arrival time and expected train arrival time for all loaded unit trains are proposed.

Findings – The proposed model is applied into a case study based on Daqin heavy haul railway. Results show that the proposed model can offer operators an optimal unit train make-up scheme for loaded direction in heavy haul railway.

Originality/value – The proposed model can offer operators an optimal unit train make-up scheme for loaded direction in heavy haul railway.

Keywords Heavy haul railway, Idling period, Loaded direction, Make-up scheme, Unit train

Paper type Research paper

© Yuqiang Wang, Yuguang Wei, Hua Shi, Xinyu Liu, Liyuan Feng and Pan Shang. Published in Smart and Resilient Transport. Published by Emerald Publishing Limited. This article is published under the Creative Commons Attribution (CC BY 4.0) licence. Anyone may reproduce, distribute, translate and create derivative works of this article (for both commercial and non-commercial purposes), subject to full attribution to the original publication and authors. The full terms of this licence may be seen at: http://creativecommons.org/licences/by/4.0/legalcode

The authors gratefully acknowledge the support provided by the national key research project “Railroad comprehensive efficiency and service level improvement technology with high-speed railway network” (Grant No. 2018YFB1201403) in China.

Conflict of interests: The authors declare that there is no conflict of interest regarding the publication of this paper.
1. Introduction
Because of the advantages of the huge capacity, high efficiency, low cost, energy saving, heavy haul railway system is considered as the future international freight transportation mode, which develops rapidly around the world (Deng and Zhao, 2014; Zhang et al., 2016). Heavy haul railway can not only alleviate the lack capacity but also greatly reduce the cost of railway transportation, especially when transporting coal and other bulk cargo.

The concept of unit train is first proposed in America. The unit train is composed of fixed locomotive and several trains. The unit train can be applied widely because of its economic benefit. In America, Canada, Australia and other countries where railway network is wide and transportation capacity is abundant, unit train can be transported, loaded and unloaded quickly, which accelerates the turnover of locomotive and trains and obtains more economic benefit. This paper focuses on the unit train that composed of fixed locomotive and several trains, thus, “train” is used to denote “unit train” for the rest of the paper.

In the freight railway network, the past research works mostly direct against on complexity of network structure and dynamic changes of transportation and production of railway, the purpose is to improve models to realize abstract description of actual adjustment and try hard to narrow the scale of the model constantly (Lin et al., 2012; Chen and Kasikitwiwat, 2011; Machado et al., 2010; Morlok and Chang, 2004; Fukasawa et al., 2002; Bojović, 2002). Because of the characteristics of the heavy haul railway, the collection, distribution, and transportation system usually have one main railway corridor to transport trains, for instance, in Daqin Railway in China. For freight train scheduling problem in a single line corridor, there have been several studies (Castillo et al., 2009; Castillo et al., 2011; Rahman, 2013; Zhou and Zhong, 2007; Rahman and Froyland, 2014). For instance, Zhou and Zhong (2007) solved the problem of scheduling trains on a single line corridor where each train only makes one origin-destination trip and used branch and bound as the solution method where two lower bound rules were introduced to reduce the search space. Deng and Zhao (2014) generated a schedule where the trains spend as little time as possible traversing between loading and unloading stations while ensuring that the interaction happen safely.

Some characteristics and operation methods in heavy haul railway, where there are large number and density of trains, but not enough capacity, need to be studied due to the particularities. Zhang et al. (2008) constructed the feedback schematic model of empty cars in unloading end of heavy haul railway, which was applied in Daqin railway. Feng and Lan (2012) studied the allocation of the trains in terms of speed, intensity and carrying capacity with a cellular automata model based on Daqin railway in China, which showed that the higher proportion of 20,000-ton trains, then the scheme would be more optimal. Fenling and Feiran (2012) studied the railway heavy haul cargo distribution and transportation system based on principal-agent theory, and proposed an incentive mechanism for railway operating companies. Dingler et al. (2014) used dispatching simulation software to analyze the effect of various combinations of intermodal and bulk trains on a hypothetical, signalized, single-track line. Upadhyay and Bolia (2014) studied the combined empty and loaded train-scheduling problem for the upcoming dedicated freight corridors in India whose model is the first of its kind to incorporate link capacity constraints in an IP formulation for this operational level problem. Zhang et al. (2016) proposed an optimization model to solve the empty wagons adjustment of heavy haul railway as a method to offer decision support to transport
enterprises on adjustment empty wagons. Zhao et al. (2010) formulated a multiple-objective model to minimize the heavy haul trains make-up time and maximize the number of heavy haul trains in the loaded duration. Han et al. (2012a) presented a model to minimize the trains waiting time and train decomposing time, then a heavy haul train make-up scheme is introduced under a determined environment. Han et al. (2012b) optimized the make-up scheme of heavy haul trains in the loading end, then a multiple-objective model is formulated to minimize the trains make-up time and running time.

From the operators' point of view, operators need to make a specific unit train make-up scheme for loaded direction, which contains the information about that how many trains need to be combined and how they are combined. The unit train make-up scheme should consider the special characteristics of the heavy haul railway and make a feasible unit train make-up scheme in loaded direction with the limited capacity of heavy haul railway corridor to minimize idling period between actual train arrival time and expected train arrival time. However, special literature is still few that study unit train make-up scheme in the heavy haul railway with limited capacity according to the characteristics of heavy haul railway. Thus, this paper based on the thought optimizing the issue of unit train make-up scheme in loaded direction in a heavy haul railway, set up a model of that for Chinese heavy haul railway.

2. Statement of the problem
2.1 Basic assumptions
Assumption 1. To ensure the uniformity of make-up trains, all trains studied in this paper are of the same type of 5,000 trains, which are widely used in real operation in Daqin railway in China.

Assumption 2. The capacity of heavy railway corridor is lack, which means that all trains cannot be transported separately during the research period. However, trains can be transported when two of them are combined, which can ensure that operators can obtain a feasible unit train make-up scheme.

2.2 Train flow organization in heavy haul railway
The mode of Chinese heavy haul railway, of which both ends connecting relevant lines in the ordinary railway network, is relatively independent in the railway network (Zhang et al., 2016). The majority of train flow needs make-up either break-up in technical station in or ends of the railways, thus form the mode of Chinese heavy haul railway, shown in Figure 1.

The collecting, distributing and transporting system has served as a platform or bond to connect transportation. It is critical to organize integrated transportation whose rapid and efficient implement requires orderly synergy between its three subsystems, i.e. collecting, transporting and distributing systems (Feng et al., 2012). The topological structure of Chinese heavy haul railway system can be described in Figure 2. The collecting and distribution system of heavy haul railway for loaded trains is composed of loading end, unloading end and heavy haul railway corridor. The loading and unloading stations are placed in two terminals of the heavy haul railway corridor. The freight is loaded in loading station, and then the loaded trains are transported to the technical stations. After the technical operation, the loaded trains can be transported to the unloading end separately or becoming a part of a combined train.

The transportation process in heavy haul railway is shown in Figure 3. In a heavy haul railway, the heavy haul railway corridor must transport all trains from loading end to unloading end. Thus, the capacity of the heavy haul railway corridor is still the bottleneck of
the whole system, which leads to that not all trains can be transported separately from loading end to unloading end. For instance in Figure 3, loaded trains can be transported separately such as Trains 1 and 4 or they can combine with other trains to form a train such as Trains 2 and 3. The make-up and break-up operations may cost additional time, however, it is necessary to make-up trains because of the limited capacity of the heavy haul railway corridor.

Thus, this paper focuses on the train flow organization for loaded direction in heavy haul railway, and proposed a model with the aim of minimizing idling period between actual train arrival time and expected train arrival time for all loaded unit trains to offer operators an optimal unit train make-up scheme.

2.3 Notation statement
The notations used in this paper are stated in this section.
Index

\( s \) = Index of stations, \( s \in S \), where \( S \) is the set of stations in the heavy haul railway system;

\( i, i' \) = Index of trains, \( i, i' \in I \), where \( I \) is the set of all trains in the research period and \( |I| \) denotes the total number of trains in the research period;

\( I^\text{load}_s \) = Set of trains, \( i \in I^\text{load}_s \), where train \( i \) loads freight at station \( s \);

\( I^\text{unload}_s \) = Set of trains, \( i \in I^\text{unload}_s \), where train \( i \) unloads freight at station \( s \).

Parameters

\( t_{\text{makeup}} \) = Train running time from loading station \( s \) to make-up technical station;

\( t_{\text{breakup}} \) = Train running time from break-up technical station to unloading station \( s \);

\( t_{\text{corridor}} \) = Train running time between technical stations in the heavy haul railway corridor;

\( t_{\text{makeup}} \) = Make-up operation time;

\( t_{\text{breakup}} \) = Break-up operation time;

\( c_{\text{corridor}} \) = Capacity of the heavy haul railway corridor in the research period;

\( c_{\text{makeup}} \) = Capacity of the make-up station in the research period;

\( c_{\text{breakup}} \) = Capacity of the break-up station in the research period;

\( T_{\text{load}}^i \) = Completing loading time of train \( i \);

\( T_{\text{unload}}^i \) = Expected unloading time of train \( i \);

\( T_{\text{makeup}}^i \) = Arrival time of train \( i \) at make-up station; and

\( T_{\text{breakup}}^i \) = Expected arrival time of train \( i \) at break-up station.

Decision variables

\( x_{ij} \) = Binary variable, which is equal to 1 if train \( i \) is combined with train \( i' \), and to 0 otherwise;

\( y_i \) = Binary variable, which is equal to 1 if train \( i \) is combined with other trains, and to 0 otherwise;

\( w_{ij} \) = Arrival time difference variables, which is the time difference between the arrival time of train \( i \) at make-up station and the arrival time of train \( i' \) at make-up station.

3. Model formulation

In Section 3, the train make-up scheme problem is formulated as a nonlinear 0-1 programming model firstly. However, this formulation makes the proposed model difficult to be solved by some standard solver packages, i.e. CPLEX. Thus, in Section 3.2, the nonlinear 0-1 programming model is reformulated into a linear 0-1 programming in Section 3.2, which can be solved directly by some standard solver packages, i.e. CPLEX.

3.1 Nonlinear 0-1 programming model

3.1.1 Objective function.

\[
\min \sum_{i, i' \in I} T_{ij}^{\text{makeup}} + y_i \left( \sum_{i' \in I} x_{ij} w_{ij} + t_{\text{makeup}}^i + t_{\text{breakup}}^i \right) + t_{\text{corridor}} - T_{ij}^{\text{breakup}} \tag{1}
\]
The actual arrival time of train \( i \) at the break-up station can be presented with 
\[
T_{i}^{\text{makeup}} + y_{i} \left( \sum_{i' \in I} x_{i'} w_{i'} + t_{i}^{\text{makeup}} + t_{i}^{\text{breakup}} \right) + t_{\text{corridor}}.
\]
This equation can be explained as that if train \( i \) is transported separately, the actual arrival time of train \( i \) at the break-up station is just \( T_{i}^{\text{makeup}} + t_{\text{corridor}} \); if train \( i \) is transported with train \( i' \) as a make-up train, additional waiting time \( w_{i'} \), make-up operation time \( t_{i}^{\text{makeup}} \), and break-up operation time \( t_{i}^{\text{breakup}} \) are cost additionally, which leads the actual arrival time of train \( i \) at the break-up station is \( T_{i}^{\text{makeup}} + w_{i'} + t_{i}^{\text{makeup}} + t_{i}^{\text{breakup}} + t_{\text{corridor}} \). Because the actual arrival time may be former or later than the expected arrival time, 
\[
\left| T_{i}^{\text{makeup}} + y_{i} \left( \sum_{i' \in I} x_{i'} w_{i'} + t_{i}^{\text{makeup}} + t_{i}^{\text{breakup}} \right) + t_{\text{corridor}} - T_{i}^{\text{breakup}} \right|
\]
is adopted to represent the idling period between actual train arrival time and expected train arrival time for train \( i \). Thus, the objective equation (1) is to minimize the idling period between actual train arrival time and expected train arrival time for all loaded trains in the research period.

3.1.2 Arrival time of trains at make-up station and expected arrival time of trains at break-up station.

\[
T_{i}^{\text{makeup}} = T_{i}^{\text{load}} + t_{s}^{\text{makeup}}, \quad \forall i \in I \cap i \in I^{\text{load}}
\]
(2)

\[
T_{i}^{\text{breakup}} = T_{i}^{\text{unload}} - t_{s}^{\text{breakup}}, \quad \forall i \in I \cap i \in I^{\text{unload}}
\]
(3)

Equations 2 and 3 are the calculation methods of arrival time \( T_{i}^{\text{makeup}} \) of train \( i \) at make-up station and expected arrival time \( T_{i}^{\text{breakup}} \) of train \( i \) at break-up station.

3.1.3 Arrival time differences of trains.

\[
w_{i'} = \left| T_{i}^{\text{makeup}} - T_{i}^{\text{makeup}} \right|, \quad \forall i, i' \in I
\]
(4)

The arrival time difference \( w_{i'} \) denotes the additional waiting time if trains \( i \) and \( i' \) are transported as a make-up train. Because trains \( i \) and \( i' \) may not arrival at the make-up station at different time, the former train need to wait the later train if they are transported as a make-up train. Thus, equation (4) defines the arrival time difference between train \( i \) and train \( i' \) at the make-up station.

3.1.4 Make-up scheme feasibility constraints.

\[
x_{i} = 0, \quad \forall i \in I
\]
(5)

\[
\sum_{i' \in I} x_{i'} \leq 1, \quad \forall i \in I
\]
(6)

\[
x_{i'} = x_{i}, \quad \forall i, i' \in I
\]
(7)
To ensure that the train make-up scheme is feasible, some constraints are adopted. Equation 5 prohibits that train $i$ can be combined with itself. Equation 6 ensures that a loaded train can be combined with one another train or transported separately. Equation 7 ensures the uniformity of the combination of trains $i$ and $i'$.

3.1.5 Capacity constraints.

$$y_i = \sum_{i' \in I} x_{i'i'}, \quad \forall i \in I$$

(8)

$$\frac{1}{2} \sum_{i \in I} y_i \leq c^{\text{makeup}}$$

(9)

$$\frac{1}{2} \sum_{i \in I} y_i \leq c^{\text{breakup}}$$

(10)

$$|I| - \frac{1}{2} \sum_{i \in I} y_i \leq c^{\text{corridor}}$$

(11)

Equation 8 defines the variable $y_i$, which denotes that whether train $i$ forms a make-up train. Equations 9 and 10 ensure that the make-up and break-up operations are limited within the make-up and break-up capacities in the research period. Equation 11 ensures that the total number of separate trains and make-up trains is limited within the capacity of the heavy haul railway corridor.

In general, the nonlinear 0-1 programming model can be stated in the following.

**[Nonlinear 0-1 programming model]**

*Objective:* Equation 1

*Subject to:* Equation 2-11.

3.2 Reformulation

The proposed model for train make-up scheme problem for loaded direction in heavy haul railway is a nonlinear 0-1 programming model, which cannot be solved directly by standard solver packages, i.e. CPLEX. Thus, in Section 3.2, the nonlinear objective function equation (1) and the nonlinear constraint equation (4) are linearized.

Firstly, some new auxiliary variables are introduced, which are used to linearize the nonlinear 0-1 programming model:

$$\alpha_{ii'} = \begin{cases} 1, & \text{if } y_i = 1 \text{ and } x_{ii'} = 1 \\ 0, & \text{otherwise} \end{cases}$$

$$\beta_i = \begin{cases} 1, & \text{if } T_i^{\text{makeup}} + y_i \left( \sum_{i' \in I} x_{i'i'} w_{i'i'} + t^{\text{makeup}} + t^{\text{breakup}} \right) + t^{\text{corridor}} \geq T_i^{\text{breakup}} \\ 0, & \text{otherwise} \end{cases}$$
The unit train make-up scheme

\[ \gamma_{i}^{d}: = \begin{cases} 
1, & \text{if } T_{i}^{\text{makeup}} \geq T_{i}^{\text{makeup}}_0 \\
0, & \text{otherwise}
\end{cases} \]

\( \delta_{i} \): Idling period between actual arrival time and expected arrival time of train

\( \text{upp } T_{i}^{\text{makeup}} \): Upper bound of variable \( T_{i}^{\text{makeup}} \).

The objective function equation (1) can be reformulated into the following formulation containing objective function equation (12) and constraints equations (13)-(17).

\[
\min \sum_{i \in I} \delta_{i} \tag{12}
\]

\[
\alpha_{i}^{d} \leq y_{i}, \ \forall i, i' \in I \tag{13}
\]

\[
\alpha_{i}^{d} \leq x_{i}, \ \forall i, i' \in I \tag{14}
\]

\[
\alpha_{i}^{d} \geq x_{i}^{d} + y_{i} - 1, \ \forall i, i' \in I \tag{15}
\]

\[
\delta_{i} \geq \left[ T_{i}^{\text{makeup}} + \sum_{i' \in I} \alpha_{i}^{d} w_{i}^{d} + y_{i} \left( t_{i}^{\text{makeup}} + t_{\text{breakup}}^{d} \right) + \mu_{\text{corridor}} \right] - T_{i}^{\text{breakup}} - (1 - \beta_{i})M \tag{16}
\]

\[
\delta_{i} \geq T_{i}^{\text{breakup}} - \left[ T_{i}^{\text{makeup}} + \sum_{i' \in I} \alpha_{i}^{d} w_{i}^{d} + y_{i} \left( t_{i}^{\text{makeup}} + t_{\text{breakup}}^{d} \right) + \mu_{\text{corridor}} \right] - \beta_{i}M \tag{17}
\]

The constraint equation (4) can be reformulated into the following formulation containing constraints equations (18)-(20).

\[
0 \leq T_{i}^{\text{makeup}} - \text{upp } T_{i}^{\text{makeup}}, \ \forall i \in I \tag{18}
\]

\[
0 \leq w_{i}^{d} - \left( T_{i}^{\text{makeup}} - T_{i}^{\text{makeup}}_0 \right) \leq 2\text{upp } T_{i}^{\text{makeup}} \left( 1 - \gamma_{i}^{d} \right), \ \forall i, i' \in I \tag{19}
\]

\[
0 \leq w_{i}^{d} - \left( T_{i}^{\text{makeup}} - T_{i}^{\text{makeup}}_0 \right) \leq 2\text{upp } T_{i}^{\text{makeup}} \gamma_{i}^{d}, \ \forall i, i' \in I \tag{20}
\]
Based on the reformulation above, the nonlinear 0-1 programming model proposed in Section 3.1 can be reformulated into a linear 0-1 programming model, which can be solved directly by the standard solver packages, i.e. CPLEX and stated in the following.

**Linear 0-1 programming model**
- Objective: Equation 12
- Subject to: Equations 2-3, 5-11 and 13-20.

### 4. Case study

#### 4.1 Basic situation introduction of the case

To prove the validity and practicability of the proposed model, a heavy haul railway system will be introduced, which consists of three loading stations, three unloading stations, one make-up technical station, and one break-up technical station, shown in Figure 4. The parameters of train running times and capacities are listed in Table I. The parameters of capacities are listed in Table II. The parameters of train demand information are listed in Table III.

#### 4.2 Computation results

The proposed model can be solved with CPLEX solver in the PC (Core i5, Frequency 3.20 GHz, Memory 16 GB) within 3 s, which means that the proposed model can be applied into a large scale problem.

The train make-up scheme for loaded direction in this case is shown in Table IV. From the make-up scheme in Table IV, we can see that to ensure all trains in the research period can be transported with the limited capacity of the heavy haul railway system, four trains are combined into two make-up trains. Then, the other eight trains can be transported separately.

### Table I.
Parameters of train running times

<table>
<thead>
<tr>
<th>Parameter</th>
<th>( t_{\text{makeup}} )</th>
<th>( t_{\text{makeup}} )</th>
<th>( t_{\text{makeup}} )</th>
<th>( t_{\text{breakup}} )</th>
<th>( t_{\text{breakup}} )</th>
<th>( t_{\text{breakup}} )</th>
<th>( t_{\text{corridor}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value (min)</td>
<td>15</td>
<td>15</td>
<td>20</td>
<td>20</td>
<td>15</td>
<td>20</td>
<td>240</td>
</tr>
</tbody>
</table>

### Table II.
Parameters of capacities

<table>
<thead>
<tr>
<th>Parameter</th>
<th>( _c_{\text{corridor}} )</th>
<th>( _c_{\text{makeup}} )</th>
<th>( _c_{\text{breakup}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>10</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>
The detailed information of the make-up scheme is listed in Table V.

4.3 Sensitivity analysis
For the unit train make-up scheme problem for loaded direction in heavy haul railway, the capacity of the heavy haul corridor and the capacities of make-up and break-up stations are two key factors, which are to be analyzed with numerical experiments further in Section 4.3.

Based on the case network and train information described in Section 4.1, 49 subproblems are designed with variable capacity of the heavy haul corridor and variable capacities of make-up and break-up stations. The capacity of the heavy haul corridor changes from 12 to 6 (denoted by the first column in Table VI), and the capacities of make-up and break-up stations change from 6 to 0 (denoted by the first row in Table VI). Each cell in Table VI represents a subproblem with a specific capacity of the heavy haul corridor and capacities of make-up and break-up stations. We can find that the decreasing of the heavy haul corridor capacity leads to the increase of the number of make-up trains, so when the corridor capacity is large enough, the optimization effect of the model is general, when the corridor capacity is extremely lacking, the optimization effect of the model is obvious.

<table>
<thead>
<tr>
<th>i</th>
<th>1</th>
<th>1</th>
<th>1</th>
<th>7:35</th>
<th>11:50</th>
<th>7:50</th>
<th>11:30</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1</td>
<td>1</td>
<td>7:45</td>
<td>12:20</td>
<td>8:00</td>
<td>12:00</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>1</td>
<td>7:55</td>
<td>12:50</td>
<td>8:10</td>
<td>12:30</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>1</td>
<td>8:15</td>
<td>13:50</td>
<td>8:30</td>
<td>13:30</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>1</td>
<td>8:20</td>
<td>14:15</td>
<td>8:35</td>
<td>13:55</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>2</td>
<td>8:25</td>
<td>13:35</td>
<td>8:40</td>
<td>12:20</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>2</td>
<td>2</td>
<td>8:35</td>
<td>14:05</td>
<td>8:50</td>
<td>12:50</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>3</td>
<td>2</td>
<td>8:50</td>
<td>13:45</td>
<td>9:10</td>
<td>13:30</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>3</td>
<td>2</td>
<td>9:10</td>
<td>14:45</td>
<td>9:30</td>
<td>14:30</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>3</td>
<td>2</td>
<td>9:30</td>
<td>13:45</td>
<td>9:50</td>
<td>13:30</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>3</td>
<td>3</td>
<td>10:00</td>
<td>14:20</td>
<td>10:20</td>
<td>14:00</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>3</td>
<td>3</td>
<td>10:10</td>
<td>14:50</td>
<td>10:30</td>
<td>14:30</td>
<td></td>
</tr>
</tbody>
</table>

Table III. Parameters of train demand information

<table>
<thead>
<tr>
<th>Train</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
</tbody>
</table>

Table IV. Make-up scheme results

Note: *Trains 4 and 5 are combined as a make-up train to be transported
To analyze the effects of the capacity of the heavy haul corridor, the subproblems whose capacities of make-up and break-up stations are six and five are taken for examples. Figures 5 and 6 show the numbers of make-up trains and idling periods for the subproblems with a capacity of the heavy haul corridor being six and five.

As Figures 5 and 6 show, the number of make-up trains and idling period are constant when the capacity of the heavy haul corridor decreases from 12 to 10. Because the optimal train make-up scheme does not use the full capacity of the heavy haul corridor. Thus, the capacity of the heavy haul corridor has no effect on the train make-up scheme when the capacity of that is from 12 to 10, which can be called “non-impact range.” However, the number of make-up trains and the idling period increase when the capacity of the heavy haul corridor is less than 10. Because no enough capacity of the heavy haul corridor can be used by the optimal train make-up scheme. Thus, there should be more make-up trains and more idling period under the lack capacity of the heavy haul corridor.

To analyze the effects of the capacities of the make-up and break-up stations, the subproblems whose capacities of the heavy haul corridor are 12 and 11 are taken for examples. Because the results of the two experiments are same, Figure 7 shows the numbers of make-up trains and idling periods for the subproblems with capacity of the heavy haul corridor being both 12 and 11.

Table V.
Detailed information of the make-up scheme

<table>
<thead>
<tr>
<th>i</th>
<th>yi</th>
<th>( T_{i}^{\text{makeup}} )</th>
<th>( T_{i}^{\text{makeup}} + y_{i} \left( \sum_{j \in I} x_{i,j} W_{ij} + T_{i}^{\text{makeup}} + T_{i}^{\text{breakup}} \right) + t_{i}^{\text{corridor}} )</th>
<th>( T_{i}^{\text{breakup}} )</th>
<th>( \delta_{i} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>7:50</td>
<td>11:50</td>
<td>11:30</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>8:00</td>
<td>12:00</td>
<td>12:00</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>8:10</td>
<td>12:10</td>
<td>12:30</td>
<td>20</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>8:30</td>
<td>13:50</td>
<td>13:30</td>
<td>20</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>8:35</td>
<td>14:10</td>
<td>13:55</td>
<td>15</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>8:40</td>
<td>12:40</td>
<td>12:20</td>
<td>20</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>8:50</td>
<td>12:50</td>
<td>12:50</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>9:10</td>
<td>13:50</td>
<td>13:30</td>
<td>20</td>
</tr>
<tr>
<td>9</td>
<td>1</td>
<td>9:30</td>
<td>14:10</td>
<td>14:30</td>
<td>20</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>9:50</td>
<td>13:50</td>
<td>13:30</td>
<td>20</td>
</tr>
<tr>
<td>11</td>
<td>0</td>
<td>10:20</td>
<td>14:20</td>
<td>14:00</td>
<td>20</td>
</tr>
<tr>
<td>12</td>
<td>0</td>
<td>10:30</td>
<td>14:30</td>
<td>14:30</td>
<td>0</td>
</tr>
</tbody>
</table>

Table VI.
Numerical analysis of impact factors on train make-up scheme

<table>
<thead>
<tr>
<th>Capacity</th>
<th>6</th>
<th>5</th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>1</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity of the heavy haul corridor</td>
<td>12</td>
<td>175 (2)*</td>
<td>175 (2)</td>
<td>175 (2)</td>
<td>175 (2)</td>
<td>215 (1)</td>
<td>320 (0)</td>
</tr>
<tr>
<td>11</td>
<td>175 (2)</td>
<td>175 (2)</td>
<td>175 (2)</td>
<td>175 (2)</td>
<td>175 (2)</td>
<td>215 (1)</td>
<td>**</td>
</tr>
<tr>
<td>10</td>
<td>175 (2)</td>
<td>175 (2)</td>
<td>175 (2)</td>
<td>175 (2)</td>
<td>175 (2)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>9</td>
<td>205 (3)</td>
<td>205 (3)</td>
<td>205 (3)</td>
<td>205 (3)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>255 (4)</td>
<td>255 (4)</td>
<td>255 (4)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>345 (5)</td>
<td>345 (5)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>475 (6)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Notes: *The idling period of the train make-up scheme for this subproblem is 175 min, and the number of make-up trains of the train make-up scheme for this subproblem is 2; **This subproblem cannot find a feasible train make-up scheme.
As Figure 7 shows, the number of make-up trains and idling period are constant when the capacities of make-up and break-up stations decreases from six to two. Because the optimal train make-up scheme does not use the full capacities of make-up and bread-up stations. Thus, the capacities of make-up and bread-up stations have no effect on the train make-up scheme when the capacities of them is from six to two, which can be called "non-impact.
range.” However, the number of make-up trains decreases and the idling period increases when the capacities of make-up and bread-up stations are less than two. Because no enough capacities of make-up and bread-up stations can be used by the optimal train make-up scheme. Thus, there should be less make-up trains and more idling period under the lack of capacities of make-up and bread-up stations.

5. Conclusions
The unit train make-up scheme problem for loaded direction in heavy haul railway is a complicated and dynamic problem. This paper firstly proposes a nonlinear 0-1 programming model for this problem, and then reformulated it into a linear 0-1 programming model with additional auxiliary variables, which can be directly solved by some standard solver packages, i.e. CPLEX. The proposed model is applied into a case study based on Daqin heavy haul railway. Results show that the proposed model can offer operators an optimal unit train make-up scheme for loaded direction in heavy haul railway. And sensitivity analysis is implemented, which can analyze the effects of the capacity of the heavy haul corridor and the capacities of make-up and break-up stations.

In the future study, we will collaboratively optimize the heavy haul trains and empty trains in the loaded and unloaded directions, respectively. In addition, the space-time network has a significant role in the train routes assignment, line planning and train scheduling, so we might integrate the space-time network and heavy haul railway in the next research. For instance, Shang, et al. (2019) formulated an approach to estimate the passengers’ flow state based on the space-time-state network by integrating Lagrangian and Eulerian observations. Shang et al. (2018) formulated a space-time-state network based on multi-commodity flow formulation to solve an equity-oriented skip-stopping schedule problem in an oversaturated urban rail transit network. Then, the linear programming model can be effectively decomposed to a least-cost sub-problem with positive arc costs for each individual passenger and a least-cost sub-problem with negative arc costs under
Lagrangian-relaxation framework. Wang et al. (2019) introduced the overnight train scheduling problem as a mixed integer linear programming (MILP) model based on a well-designed time-discretized space-time network, then a decomposition method based on Lagrangian relaxation is presented to solve the large-scale experiment.

References


Corresponding author
Pan Shang can be contacted at: 478054648@qq.com

For instructions on how to order reprints of this article, please visit our website:
www.emeraldgrouppublishing.com/licensing/reprints.htm
Or contact us for further details: permissions@emeraldinsight.com