Optimizing the Utilization Plan of CRH-Emu with Particle Swarm Algorithm

Zhong-kai WANG¹, Tian-yun SHI¹, Wei-jiao ZHANG¹*, Fan LI¹ and Fei LV¹

¹Institute of Computing Technologies
China Academy of Railway Sciences, Beijing, China
winter-light@163.com
*Corresponding author

Keywords: CRH-emu transportation organization, Transportation optimization, Utilization plan of crh-emu, Particle swarm optimization.

Abstract. China Railway High-speed is expanding dramatically recently. The utilization plan of China Railway High-speed Electric Multiple Unit (CRH-Emu) train plays the basic role in the routine transportation organization of high-speed railway. Because the plan is interacted with CRH-Emu's off-line repair plan and influenced by many other factors, it is a rather complicated task for CRH-Emu Depot to schedule it manually. In order to obtain optimal long-term solution to instead manual operation, this paper established an integer model, with balancing CRH-Emu’s future repair workload as the objective function, and with the transportation demand, off-line repair regulation, and depot's repair capacity as the constraints. By separating the mutual influencing factors between on-line utilization and off-line repair plans, the original problem became easier to resolve. The particle swarm optimization algorithm was applied to solve the model. Furthermore, a testing example was given to testify the model and algorithm, and the result showed that the proposed method could obtain desirable solutions and assist CRH-Emu Depot to manipulate Emu’s daily organization.

Introduction

China's high speed railway is developing into a huge network covering most of its middle scale cities. By the recent convey there are over 1800 China Railway High-speed Electric Multiple Unit (CRH-Emu) trains that come into service every day across China up to this December. To guarantee the operational security of CRH-Emu, 45 Emu depots were constructed to carry out CRH-Emu's daily operation and repair which includes Level-1 and Level-2 by the Railway CRH-Emu operational and repair regulation.

CRH-Emu's daily transportation organization is mainly embodied by its on-line utilization plan which on the premise of high-speed train diagram, schedules which CRH-Emu is going to take on a special transportation task. Because the plan has great impact on the interest of high-speed railway, it is very critical to utilize CRH-Emu more efficiently.

In practice, however, the plan is often affected by many factors; manually obtaining optimal solution is increasingly difficult. Therefore, to provide automatic planning method becomes a very urgent requirement of CRH-Emu depot and this paper was motivated.

The Railway CRH-Emu operational and repair regulation is listed in article [1]. Several works related to the optimization of CRH-Emu utilization plan should be mentioned first. It was proved that railway train operational optimization problem is NP-hard [2]. P. Zhao analyzed the CRH-Emu transportation organization method, and proposed the basic optimization models for scheduling CRH-Emu's utilization, repair and crew plans [3]. Y. Wang adopted mathematical algorithm to solve rolling stock planning and crew planning problems [4]. Several heuristic algorithms were proposed to obtain optimal solution for the plans [5-10]. Z. Wang proposed mathematical models and solving methods for scheduling CRH-Emu's operation plan and repair plan within one process [11, 12]. H. Li and L. Tong discussed the universal solving models and algorithms for CRH-Emu's scheduling
problems [13, 14]. Dedicated to CRH-Emu's transportation organization problem, these works achieved many results. But for CRH-Emu depots, many practical factors involved restrain the direct application of those theories. In order to provide more effective method for depots' practice, this paper was motivated.

This paper is organized as follows: Section 2 describes the CRH-Emu's utilization plan. Section 3 provides the mathematical model. A solving algorithm based of particle swarm algorithm is deployed in section 4. A testing example and conclusions are presented in section 5 and 6, respectively.

**Optimizing Problem of Scheduling CRH-Emu Utilization Plan**

**Transportation Organization of China Railway High-speed**

The transportation organization of China Railway High-speed is mainly separated by two phases:

**Draw up Railway Train Diagram.** Railway Train Diagram is the very core of railway's transportation organization. The diagram formulates the details of every passenger train, such as the departure/arrival railway station, departure/arrival time, speed and so on.

Every year, China Railway Cooperation organizes related department to schedule the diagram, and publishes it to CRH-Emu Depots as standard.

**Implement Railway Train Diagram.** It is the CRH-Emu Depot's job to implement the given Train Diagram. For CRH-Emu Depots, they have several different types of CRH-Emus as resource to deploy, and take on part of the train diagram as transportation task to complete. The transportation organization of CRH-Emu Depot can be described by utilization plan.

In this paper, we assume that the Railway Train Diagram is fixed, and discuss the optimization problem of CRH-Emu Depot's utilization plan.

**CRH-Emu Depot's Utilization Plan**

The CRH-Emu Depot's utilization plan is to assign ready-to-online CRH-Emu for every transportation task given by Railway Train Diagram.

We take Beijing South Depot as an example. The depot is located in the southern part of Beijing, and mainly dedicated to the transportation from Beijing to Guangzhou, Shanghai, and Tianjin high-speed passenger line.

Table 1 lists three types of CRH-Emu of the Beijing South Depot.

<table>
<thead>
<tr>
<th>Emu Type</th>
<th>CRH-Emu Trains</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRH2E</td>
<td>CRH2E-2122, CRH2E-2124, CRH2E-2125, CRH2E-2126, CRH2E-2127, CRH2E-2128, CRH2E-2129, CRH2E-2106, CRH2E-2107, CRH2E-2118, CRH2E-2119, CRH2E-2110</td>
</tr>
<tr>
<td>CRH3C</td>
<td>CRH3C-3030, CRH3C-3181, CRH3C-3183, CRH3C-3185, CRH3C-3187, CRH3C-3190, CRH3C-3194, CRH3C-3196, CRH3C-3197</td>
</tr>
</tbody>
</table>

The Train Diagram describes all the passenger trains within 24 hours. For the convenience of transportation organization, passenger trains are usually connected into transportation route according to some special rules.

As a result, CRH-Emu Depot can deal with transportation route as the direct task to be satisfied. Their job is to assign suitable CRH-Emu to implement all the transportation routes of each day.
Fig. 1 demonstrates part of the Train Diagram. From the figure, we can see the route "RD1010" includes passenger trains "G101-G1023-G2102-G190", and the route "RH2010", consists of "G101-G1023-G2102-G190".

Here, we organize five days' utilization plan as an example of Beijing South Depot.

Fig. 2 demonstrates four CRH-Emu's utilization plan during five days. CRH2E-2122 is scheduled to take RD1010 on day1, day2, day3, and day5, while it must get off-lined to proceed repair because of the repair cycle bounds restraints. Therefore, the transportation task RD1010 on day4 can't be satisfied unless CRH2E-2126 takes on the missing task.

Additionally, we can see the CRH3C-3181's repair work lasts for three days.

Besides, the transportation route RC200 needs two days to complete.

**Operational Restraints of Utilization Plan**

Generally, there are three restraints of utilization plan.

To find a suitable CRH-Emu for all the route on each day. That constraint means none of the route-day shall be missed.

"Suitable" means the CRH-Emu must match the route. The specific conditions are: CRH-Emu type, heading direction, and passenger capacity.

There must be certain number of hot standby CRH-Emu each day, in order to prepare for unpredictable accidents.

**Repair Restraints of Utilization Plan**

According to the Railway CRH-Emu operational and repair regulation [1], defined by China Railway Cooperation, not all the Emus are available for on-line operation during the same time, since those Emus which reach their repair cycle must get off-lined and repaired.

Table 2 gives a short introduction of repair packets of Beijing South Depot.
Table 2. Repair packets of Beijing South Depot.

<table>
<thead>
<tr>
<th>Repair Packet</th>
<th>Repair Cycle (days/kkm)</th>
<th>Consume Time</th>
<th>Dedicated Emu Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>2M</td>
<td>45/33</td>
<td>5 (h)</td>
<td>CRH2E/ CRH380AL</td>
</tr>
<tr>
<td>Hollow shaft Detection (HSD)</td>
<td>--/250</td>
<td>5 (h)</td>
<td>CRH2E/ CRH380AL</td>
</tr>
<tr>
<td>Wheel repair (WR)</td>
<td>--/250</td>
<td>8 (h)</td>
<td>CRH2E/ CRH380AL</td>
</tr>
<tr>
<td>LU Detection(LU)</td>
<td>--/200</td>
<td>10 (h)</td>
<td>CRH2E/ CRH380AL</td>
</tr>
<tr>
<td>Gear box Oiling(GBX)</td>
<td>360/360</td>
<td>12 (h)</td>
<td>CRH2E/ CRH380AL</td>
</tr>
<tr>
<td>3M</td>
<td>30/30</td>
<td>3 (h)</td>
<td>CRH3C</td>
</tr>
<tr>
<td>Hollow shaft Detection(HSD)</td>
<td>250</td>
<td>3 (h)</td>
<td>CRH3C</td>
</tr>
<tr>
<td>Wheel repair(WR)</td>
<td>--/200</td>
<td>8 (h)</td>
<td>CRH3C</td>
</tr>
<tr>
<td>LU Detection(LU)</td>
<td>--/60</td>
<td>8 (h)</td>
<td>CRH3C</td>
</tr>
<tr>
<td>Gear box Oiling(GBX)</td>
<td>--/60</td>
<td>8 (h)</td>
<td>CRH3C</td>
</tr>
</tbody>
</table>

The specific repair restraints are listed as follow:

**Repair Cycle Bounds.** The repair cycles of packets include two parts: time cycle and mileage cycle. If any of the packets of a CRH-Emu reaches either time or mileage cycle, the CRH-Emu has to proceed repair.

We must note that both the time and mileage cycle are related with utilization plan. If either the time or the mileage value accumulated by utilization plan reaches the packet cycle bound, the packet needs to proceed repair.

**Repair Cycle Tolerance.** Additional, there exists a tolerance range (from minus 10% to plus 10% of the cycle value) for each packets. If a CRH-Emu reach the floor limit, it can be repaired. Correspondingly, any CRH-Emu that oversteps ceiling limit of repair cycle means overdue repair and strictly forbidden.

**The Latest Repair Records.** The latest repair records define what day and how many miles a CRH-Emu's packet got repaired. Those data are the very initial points to calculate repair plan.

**The Optimization Objective of Utilization Plan**

For any depots, the number of CRH-Emus that can be handled is limited. If the number of CRH-Emus to proceed repair exceeds the threshold during a period, those depots do not have enough CRH-Emus to satisfy transportation demand.

Given the fact that the utilization plan decides the result of both the time and the mileage value, the repair date of CRH-Emu is influenced by the utilization plan. Therefore, the optimization objective of utilization plan is to balance the future CRH-Emu repair time, so that the future transportation organization of depot can get better.

**Model Formulation**

We describe the notation used in the model.

**Sets**

- **E**: The set of CRH-Emu trains, with the maximum number of \( N_E \). Each CRH-Emu train is represented by variable \( e (e=0, \ldots, N_E) \).
- **D**: The set of days to be planed. The maximum number of that set is defined by the parameter \( N_D \), and each day in that set is defined by variable \( d (d=0, \ldots, N_D) \).
\(P\): The set of packets. The maximum number of that set is defined by the parameter \(N_P\), and each packet in that set is defined by variable \(p (p=0, \ldots, N_P)\).

\(P_e\): The set of packets dedicated to CRH-Emu \(e\).

\(R\): The set of route given by passenger train diagram. The maximum number of that set is defined by the parameter \(N_R\), and each packet in that set is defined by variable \(r (r=0, \ldots, N_R)\).

**Variables**

- \(t_{ep}\): The latest repair time of CRH-Emu \(e\) on packet \(p\).
- \(m_{ep}\): The latest repair mileage of CRH-Emu \(e\) on packet \(p\).
- \(C_p^T\): The time cycle of packet \(p\).
- \(C_p^M\): The mile cycle of packet \(p\).
- \(D_d\): The number of hot standby CRH-Emus of day \(d\).
- \(\theta_{er}\): when the CRH-Emu \(e\) matches route \(r\), \(\theta_{er}\) equals to 1, otherwise to 0.
- \(m_r\): The on-line running mileage of route \(r\).
- \(t_r\): The on-line running time of route \(r\).
- \(\phi_{ep}\): Repair date of CRH-Emu under repair packet \(p\).

\[\lambda(d, \phi_{ep})\]: If CRH-Emu \(e\) is off-line on day \(d\) and proceed repair of packet \(p\), \(\lambda(d, \phi_{ep})\) equals to 1, otherwise to 0.

**Decision Variables**

- \(x_{erd}\): If CRH-Emu \(e\) is on-line on day \(d\) and take on the transportation route \(r\), \(x_{erd}\) equals to 1, otherwise to 0.

**Model Formula**

The objective function and constrained conditions can be established as follows.

\[
Z = \sum_{d \in D} \left( \sum_{e \in E} \sum_{p \in \mathcal{P}} \lambda(d, \phi_{ep}) - \mu \right)^2
\]  

\[\text{S.T.}\]

\[
\sum_{e \in E} x_{erd} = 1 \quad \forall r \in R, \forall d \in D
\]  

\[
\sum_{r \in R} x_{erd} \leq 1 \quad \forall e \in E, \forall d \in D
\]  

\[
x_{erd} \leq \theta_{er} \quad \forall e \in E, \forall d \in D, \forall r \in R
\]  

\[
\sum_{e \in E} x_{eld} = H_d \quad \forall d \in D
\]  

\[
\sum_{d=i}^{j} x_{erd} t_r \leq 1.1 \left( C_p^T + \sum_{d=i}^{j} \lambda(d, \phi_{ep}) \right) \quad \forall e \in E, p \in P, i, j \in D, i < j
\]  

where \(\mathcal{P}\) is the set of packets.
The objective of the model is to balance future repair (1). The formula (2-4) ensure that operational constraints. (5) is the hot standby restraint. The constraints (6-9) guarantee that there is no packets of any CRH-Emu overstep their repair ceiling cycle.

Optimization Algorithm with Particle Swarm Algorithm

Because the model in section III is NP-hard, and the number of CRH-Emus is usually very large, it is difficult to get the precise solution. Therefore, we dedicate to find a good solution within acceptable time.

Model Pre-Processing

**Drop hot Standby Restraint.** To decrease the model scale, we consider hot standby constraint as a common route. Then, the constraint (4) in model proposed by section III can be summarized into constraint (1).

**Decrease Repair Restraint.** Usually speaking, the repair cycles of most packets are very large compared with the date range to be planed. We can tell this fact from the Table II mentioned in section II.

For example, if the date range to be planed is relatively small, those packets with much larger cycle bounds won’t appear twice during the planed date range for the same CRH-Emu.

Therefore, the repair cycle bounds restraints of (6) and (7) in the model above can be dropped. After the model pre-processing, the model above can be simplified as the following model.

Min

\[
Z = \sum_{d \in D}\left(\sum_{e \in E_{P}} \sum_{p \in P} \lambda(d, \varphi_{pe}) - \mu \right)^2
\]

\[\sum_{e \in E_{P}} x_{ed} = 1 \quad \forall r \in R \cup H_d, \forall d \in D \quad (12)\]

\[\sum_{r \in R} x_{ed} \leq 1 \quad \forall e \in E, \forall d \in D \quad (13)\]
\[ x_{erd} \leq \theta_{er} \quad \forall e \in E, \forall d \in D, \forall r \in R \]  

\[ t^0_{ep} + \sum_{d=1}^{j} x_{erd} t_r \leq 1.1 C_p^T (1 + \sum_{d=1}^{j} \lambda (d, \varphi_{ep})) \quad \forall e \in E, p \in P, j \in D \]  

\[ m^0_{ep} + \sum_{d=1}^{j} x_{erd} m_r \leq 1.1 C_p^M (1 + \sum_{d=1}^{j} \lambda (d, \varphi_{ep})) \quad \forall e \in E, p \in P, j \in D \]  

\[ x_{erd}, \lambda (d, \varphi_{ep}) = 0.1 \]  

**Application of Particle Swarm Algorithm.** We set the number of particle \( N_P \). And there exists a vector for each particle \( p \) to describe the position of the particle. According to the model above, we use the position of particle \( X_p = (x_{1p}, \ldots, x_{Np}) \) to represent a solution. And each dimension in the vector represents an assignment of CRH-Emu to route. According to the basic principle of particle swarm algorithm, we deploy vector \( V_p = (v_{1p}, \ldots, v_{Np}) \) to describe the velocity of particle \( p \). Additionally, we deploy vector \( P_p = (p_{1p}, \ldots, p_{Np}) \) to record the best position of particle \( p \) during its searching process. Finally, vector \( P_q = (p_{1q}, \ldots, p_{Nq}) \) is defined to represent the best solution among particles.

**Rules of Particle Swarm Algorithm**

**Iteration Rule.** The dimension of every particle is defined by variable \( J = NE ND \) \((\text{NR} + \text{Hd}) \). The velocity of every particle \( p \) is updated by formula (18) [15].

\[ v_{qj}^{(t+1)} = \omega_{q}^{(t)} v_{qj}^{(t)} + c_1 r_1 (p_{qj}^{(t)} - x_{qj}^{(t)}) + c_2 r_2 (p_{qj}^{(t)} - x_{qj}^{(t)}) \]  

\( t \) is iteration variable. \( r_1 \) and \( r_2 \) are random values restrained between [0,1]. The variable \( \omega_q \) is decided by formula (19).

\[ \omega_q^{(t)} = \omega_{max} \frac{t_{max} - t}{t_{max}} \times t \]  

Additionally, we bound the value of \( v_{qj}^{(t+1)} \) within \([v_{max}, v_{min}]\).

2) Decision Variable Rule

The decision variable \( x_{erd} \) is calculated by the formula (20).

\[ x_{qj}^{(t+1)} = \begin{cases} 1, & \rho \leq \text{sig}(v_{qj}^{(t+1)}) \\ 0, & \text{other} \end{cases} \]  

Where, \( \rho \) is also a random value restrained between [0,1].
Algorithm Description

Here, the algorithm description is given.

Algorithm I: Optimize Utilization Plan with Particle Swarm Algorithm

Model pre-processing
Input the sets of CRH-Emu, Route, Packet, Day
Initialize position, velocity of particles
Initialize optimal position of each particle according to model objective function
Initialize optimal position among particles
While iteration variable $n$ < maximum iteration count
  While particle $p$ < maximum particle count
    Update velocity of particle $p$
    Update position of particle $p$
    Calculate model objective function of particle $p$
    Update optimal position of particle $p$
    Update optimal position among particles
output optimized utilization plan

Model Testing

In this section, we test the model and algorithm by the practical example of Beijing South Depot mentioned above.

The input data are as follows:

The set of CRH-Emus is listed by Table 1.
The repair packet regulation by Table 2.

Table 3. Route list of Beijing South Depot.

<table>
<thead>
<tr>
<th>Route</th>
<th>Run Time(min)</th>
<th>Run Mile (km)</th>
<th>Emu Type Required</th>
<th>Lasting Days</th>
</tr>
</thead>
<tbody>
<tr>
<td>C2211</td>
<td>1351</td>
<td>3276</td>
<td>CRH3C</td>
<td>2</td>
</tr>
<tr>
<td>C2287</td>
<td>1696</td>
<td>3836</td>
<td>CRH3C</td>
<td>2</td>
</tr>
<tr>
<td>C3059</td>
<td>710</td>
<td>1332</td>
<td>CRH3C</td>
<td>1</td>
</tr>
<tr>
<td>C2111</td>
<td>1581</td>
<td>3276</td>
<td>CRH3C</td>
<td>2</td>
</tr>
<tr>
<td>C2587</td>
<td>599</td>
<td>3836</td>
<td>CRH3C</td>
<td>1</td>
</tr>
<tr>
<td>D355</td>
<td>910</td>
<td>1332</td>
<td>CRH2E</td>
<td>1</td>
</tr>
<tr>
<td>D355</td>
<td>1810</td>
<td>3332</td>
<td>CRH2E</td>
<td>2</td>
</tr>
<tr>
<td>D931</td>
<td>1953</td>
<td>4604</td>
<td>CRH2E</td>
<td>2</td>
</tr>
<tr>
<td>D935</td>
<td>1973</td>
<td>4606</td>
<td>CRH2E</td>
<td>2</td>
</tr>
<tr>
<td>D905</td>
<td>1878</td>
<td>4446</td>
<td>CRH2E</td>
<td>2</td>
</tr>
<tr>
<td>D907</td>
<td>1862</td>
<td>4266</td>
<td>CRH2E</td>
<td>2</td>
</tr>
<tr>
<td>G941</td>
<td>1942</td>
<td>4732</td>
<td>CRH380AL</td>
<td>2</td>
</tr>
<tr>
<td>G941</td>
<td>1942</td>
<td>4732</td>
<td>CRH380AL</td>
<td>2</td>
</tr>
<tr>
<td>G3001</td>
<td>764</td>
<td>1674</td>
<td>CRH380AL</td>
<td>1</td>
</tr>
<tr>
<td>G2205</td>
<td>1763</td>
<td>3996</td>
<td>CRH380AL</td>
<td>2</td>
</tr>
<tr>
<td>G3071</td>
<td>1736</td>
<td>3777</td>
<td>CRH380AL</td>
<td>2</td>
</tr>
<tr>
<td>G2233</td>
<td>1573</td>
<td>3326</td>
<td>CRH380AL</td>
<td>2</td>
</tr>
<tr>
<td>G2290</td>
<td>1551</td>
<td>3276</td>
<td>CRH380AL</td>
<td>2</td>
</tr>
<tr>
<td>G3067</td>
<td>769</td>
<td>1670</td>
<td>CRH380AL</td>
<td>1</td>
</tr>
</tbody>
</table>
Table 4. Repair record.

<table>
<thead>
<tr>
<th>Emus</th>
<th>GBO</th>
<th>LU</th>
<th>WR</th>
<th>HSD</th>
<th>2M</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRH2E-2124</td>
<td>2795636/15-08-02</td>
<td>2785960/15-07-26</td>
<td>2766654/15-07-05</td>
<td>2590732/15-02-02</td>
<td>2966216/15-11-22</td>
</tr>
<tr>
<td>CRH2E-2125</td>
<td>2775733/15-09-25</td>
<td>2767103/15-09-11</td>
<td>2647843/15-06-05</td>
<td>2731198/15-08-14</td>
<td>2845627/15-11-09</td>
</tr>
<tr>
<td>CRH2E-2128</td>
<td>2715438/15-09-05</td>
<td>2684810/15-08-16</td>
<td>2780913/15-10-14</td>
<td>2487942/15-05-08</td>
<td>2814173/15-11-16</td>
</tr>
</tbody>
</table>

The set of transportation routes by Table 3.
The part of last repair record by Table 4.

We planned utilization plan of the range from Dec/01/2015 to Dec/25/2015.
If Beijing South Depot calculates its CRH-Emu utilization plan directly, there will be many CRH-Emus that reach their repair packet cycle bounds during relatively centralized days and have to get off-line. As a result, there shall be not enough CRH-Emus to complete transportation task. Fig. 3 shows the future CRH-Emu off-line numbers and repair packet amount. We can tell that from Dec/15/2015 to Dec/21/2015 the amount of off-lined CRH-Emus overstepped the tolerance.

![Figure 3. Off-lined CRH-Emus and Repair Distribution without Optimization.](image)

By balancing the repair Time, the algorithm distributed those CRH-Emus that were supposed to get repaired during the days from Dec/15/2015 to Dec/29/2015. Fig. 4 demonstrates the result.
Summary
With the development of China's high speed railway, the number of CRH-Emu deployed into railway network is increasing dramatically. How to organize the transportation of CRH-Emu more efficiently becomes a problem for China Railway Cooperation. Optimizing the utilization plan of CRH-Emu is one of the important strategies to improve the benefit of railway industry.

In this paper, we gave a short introduction of the transportation organization of CRH-Emu, analyzed the influence factor of utilization plan, built a mathematical model to optimize the plan, and designed the solving algorithm based on particle swarm algorithm.

Acknowledgment
This work was supported by China Railway Corporation Science and Technology Project under Grant Number 2014J006-C.

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