Reconstruction and operational direction schedules of mine lanes with mixed-mine truck flow for efficiency improvement

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ABSTRACT

Temporal and spatial imbalances in truck flow often occur in mining operations due to fluctuating production demands and varying operational conditions. In current mining road systems, lane directions are typically unrestricted, allowing trucks to travel in both directions. However, each lane can only be occupied by one truck at a time, leading to congestion on certain roads while others remain underutilized. To address this issue, this paper proposes a novel approach that imposes directional restrictions on mine lanes and introduces operational direction schedules to optimize mixed-mine truck flow. A bi-level programming model is formulated to solve this problem, incorporating both the reconstruction of mine lanes and the scheduling of their operational directions. In the upper-level model, the number of controlled mine lanes and scheduling plans are determined to minimize the total operational cost. The lower-level model captures the behavior of mixed-mine truck flow, where both connected autonomous mine trucks (CAMTs) and connected human-driven mine trucks (CHMTs) follow a user equilibrium principle. Factors such as value of time (VOT) and fuel consumption are included in the generalized cost function. A numerical example based on a typical mining network is conducted to illustrate the effectiveness of the proposed solution. The results indicate that the introduction of operational direction schedules can significantly improve the overall efficiency of the mining transportation system.

Keywords: Mine lanes; mixed-mine truck flow; reconstruction strategy; operational direction schedules; operational efficiency improvement

1. INTRODUCTION

In mining operations, temporal and spatial imbalances in truck flow frequently occur due to fluctuating production activities, variable operational conditions, and equipment usage schedules. These imbalances can lead to congestion in certain mining roads where the number of mine trucks is huge, while other routes remain underutilized, resulting in inefficiencies and increased operational costs. Typically, mining roads allow trucks to travel in both directions, but each lane can only be occupied by one truck at a time due to safety concerns. This unrestricted use of lanes, without proper control of mine truck direction, can exacerbate congestion on busy routes and create an inefficient use of available road capacity. To address these challenges, it is crucial to reconstruct certain mining lanes and control the direction of truck flow on these lanes, for instance, by deploying signal lights to manage the lane directions. By regulating lane directions and establishing time-dependent operational direction schedules, it is possible to alleviate congestion and enhance the overall efficiency of the mining transportation system.

Over the years, many studies have focused on improving road utilization and mine truck flow management in various sectors, but there is limited research on the specific needs of mixed-mine truck flow in mining operations, where both autonomous mine trucks (AMTs) and human-driven mine trucks (HMTs) coexist[1]-[3]. The operational characteristics of AMTs differ significantly from those of HMTs, particularly in terms of speed, safety protocols, and decision-making processes[4]-[5]. This introduces new complexities in managing mine truck flow, especially when determining optimal lane usage and direction scheduling[6]-[7]. Traditional approaches that treat all mine trucks homogeneously are inadequate for addressing the unique requirements of mixed-mine trucks transportation systems. To optimize the flow of both AMTs and HMTs, it is necessary to reconstruct lane management strategies and introduce operational direction schedules that account for the varying operational demands. Implementing such a system would not only improve mine truck flow efficiency but also enhance overall productivity and reduce operational costs in mining environments.

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This paper investigates the problem of optimizing lane direction control and operation schedules in a mixed-mine truck flow environment, where both connected autonomous mine trucks (CAMTs) and connected human-driven mine trucks (CHMTs) are involved simultaneously. The main contributions of this paper are as follows: Firstly, we propose a novel approach that introduces lane direction control and operational schedules to address the temporal and spatial imbalances of mixed-mine truck flow in mining operations. By restricting and scheduling lane directions dynamically, we aim to improve road utilization and reduce congestion caused by uneven distribution of mixed-mine truck flow. Secondly, a bi-level programming model is developed to optimize the reconstruction strategy and the operational direction schedules. In the upper-level model, the number of controlled mine lanes and schedules are determined to minimize total operational costs, while in the lower-level model, we capture the behavior of mixed-mine truck flow consisting of CAMTs and CHMTs. The model accounts for factors such as the VOT and fuel consumption in the generalized cost function, reflecting the differences between CAMTs and CHMTs. Thirdly, we conduct a numerical case study based on a typical mining transportation network to demonstrate the effectiveness of the proposed solution. The results show that implementing operational direction schedules and lane control can significantly enhance the efficiency of mixed-mine truck flow, reducing overall operational costs and improving productivity.

2. MATHEMATICAL FORMULATION

The reconstruction and operational direction schedules problem of mine lanes with CAMTs and CHMTs simultaneously is built as a bi-level programming model. We divide the planning time horizon into several time intervals. The specific operational direction schedules of mine lanes is developed within each time interval. The proposed problem can be described as follows: A directed graph $G(N,A)$ is defined to represent the mine transportation network, where the node set N includes all intersections in the mine transportation network, and arc set A denotes the set of all lanes. Let $M=\{1,2\}$ denotes the set of different types of mine trucks, where $m=1$ represents CAMTs, and $m=2$ represents CHMTs. t_a^h depicts the travel time on lane a within time interval h, which is associated with the mixed-mine truck flow consisting of CAMTs and CHMTs. Not only the reconstruction strategy of mine lanes, but also the operational direction schedules of mine lanes in a given planning time horizon H are determined simultaneously. The mine transportation network can be illustrated as Figure 1.

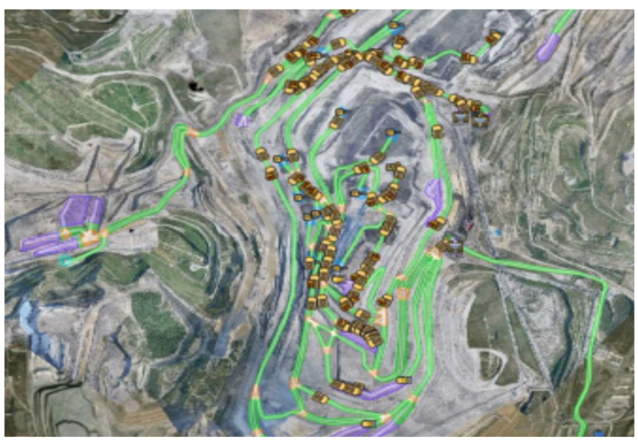


Figure 1. An illustrated example for the mine transportation network.

2.1. Network equilibrium model with mixed-mine truck flow

In this paper, we assume that AMTs and HMTs are connected trucks, namely CAMTs and CHMTs respectively. And they can access to the real-time information in the mine transportation network, such as congested road segments and accident spots. Then, all CAMTs and CHMTs would choose their routes based on user equilibrium principle. We adopt equation (1) to describe the travel time of CAMTs and CHMTs on lane a, which is a strictly monotone increasing function to the lane flow.

$$t_a^h\left(v_a^{h1},v_a^{h2}\right)=\frac{l_a}{S_a}\left[1+\left(\frac{v_a^{h1}+v_a^{h2}}{Q_a}\right)^4\right] \tag{1}$$

The driving behaviors of CAMTs and CHMTs are different. Compared to CHMTs, CAMTs could take quicker reactions. Moreover, CAMTs can maintain reduced headways with the trucks in front of them. Since the headways of CAMTs are smaller than the CHMTs, the road capacity will be improved. Levin and Boyles[8] considered the capacity of lane a was influenced by the ratio of CAMTs. They assumed that all CAMTs were with same reaction time τ_1, and reaction time of all CHMTs were τ_2. Then, the capacity on lane a ($a \in A$) with mixed-mine truck flows can be calculated as follows:

$$Q_a = S_a \cdot \frac{1}{S_a\left(\frac{v_a^{h1}}{v_a^{h1}+v_a^{h2}}\tau_1 + \frac{v_a^{h2}}{v_a^{h1}+v_a^{h2}}\tau_2\right)+\xi} \tag{2}$$

When only CAMTs are involved in the mine transportation network, then the relationship of mine truck flow $v_a^{h1} = v_a^{h1} + v_a^{h2}$ can be obtained. Hence, the capacity Q_{a1} of each lane a ($a \in A$) can be calculated as follows:

$$\begin{aligned}\left(n_a+\mu_a^h\right)\cdot Q_{a1} &= S_a \cdot \frac{1}{S_a\left(\frac{v_a^{h1}}{v_a^{h1}+v_a^{h2}}\tau_1 + \frac{v_a^{h1}}{v_a^{h1}+v_a^{h2}}\tau_2\right)+\xi} \\ &= S_a \cdot \frac{1}{S_a\tau_1+\xi}\end{aligned} \tag{3}$$

Similarly, we can obtain the capacity Q_{a2} of each lane a ($a \in A$), when only CHMTs are involved in the mine transportation network:

$$\left(n_a+\mu_a^h\right)\cdot Q_{a2} = S_a \cdot \frac{1}{S_a\tau_2+\xi} \tag{4}$$

According to equations (3) and (4), reaction time of CAMTs and CHMTs can be calculated as follows:

$$\tau_1 = \frac{1}{\left(n_a+\mu_a^h\right)\cdot Q_{a1}} - \frac{\xi}{S_a} \tag{5}$$

$$\tau_2 = \frac{1}{\left(n_a+\mu_a^h\right)\cdot Q_{a2}} - \frac{\xi}{S_a} \tag{6}$$

Substituting equations (2), (5) and (6) into equations (1), which yields travel time on lane a:

$$\begin{aligned}t_a^h\left(v_a^{h1},v_a^{h2}\right) &= \frac{l_a}{S_a}\cdot\left\{1+\left\{\left(v_a^{h1}+v_a^{h2}\right)\cdot\left[\frac{v_a^{h1}}{v_a^{h1}+v_a^{h2}}\cdot\frac{1}{\left(n_a+\mu_a^h\right)\cdot Q_{a1}}+\frac{v_a^{h2}}{v_a^{h1}+v_a^{h2}}\cdot\frac{1}{\left(n_a+\mu_a^h\right)\cdot Q_{a2}}\right]\right\}^4\right\} \\ &= \frac{l_a}{S_a}\cdot\left\{1+\left[\frac{1}{n_a+\mu_a^h}\left(\frac{v_a^{h1}}{Q_{a1}}+\frac{v_a^{h2}}{Q_{a2}}\right)\right]^4\right\}\end{aligned} \tag{7}$$

Since there are some difference in CAMTs and CHMTs, a generalized travel cost function is adopted in the proposed problem to figure out the travel cost of CAMTs and CHMTs. The VOT has an impact on the travel route choices. In addition, fuel cost is another factor to influence the travel route choices. Taiebat et al.[9] found that CAMTs could improve the energy efficiency and reduce the fuel cost. We incorporate the VOT and fuel consumption into the travel cost function to calculate the travel cost of CAMTs and CHMTs respectively. Hence, the travel cost $\tilde{t}_a^{hm}\left(v_a^{h1},v_a^{h2}\right)$ of CAMTs and CHMTs on lane a can be formulated as follows:

$$\tilde{t}_a^{hm}\left(v_a^{h1},v_a^{h2}\right) = t_a^h\left(v_a^{h1},v_a^{h2}\right)\cdot VOT_m + \vartheta_m\cdot\varphi\cdot E_a \tag{8}$$

The VOT of mine truck type m is represented by VOT_m. Parameter E_a denotes the fuel consumption of each mine truck on lane a. The unit price of fuel is depicted by parameter φ. Parameter ϑ_m is the rate of fuel consumption of mine truck type m. Here, equation (8) is also a strictly monotone increasing function to lane flow of either CAMTs or

CHMTs. Then, the network equilibrium model is then formulated as:

[NE-MTF-h]:

$$\boldsymbol{\Delta}\mathbf{x}_w^{hm} = \mathbf{E}_w q_w^{hm} \qquad \forall m \in M,\ w \in W, h \in H\infty \tag{9}$$

$$x_{wa}^{hm} \geq 0 \qquad \forall a \in A, m \in M, w \in W, h \in H \tag{10}$$

$$v_a^{hm} = \sum\nolimits_{w \in W} x_{wa}^{hm}, \forall a \in A \qquad w \in W, h \in H \tag{11}$$

$$\tilde{t}_a^{hm}\left(v_a^{h1}, v_a^{h2}\right) + \rho_{w,i}^{hm} - \rho_{w,j}^{hm} - \eta_{w,a}^{hm} = 0 \qquad \forall a \in A, m \in M, w \in W, h \in H \tag{12}$$

$$\eta_{w,a}^{hm} \cdot x_{wa}^{hm} = 0 \qquad \forall a \in A, m \in M, w \in W, h \in H \tag{13}$$

$$\eta_{w,a}^{hm} \geq 0 \qquad \forall a \in A, m \in M, w \in W, h \in H \tag{14}$$

Where $\boldsymbol{\Delta}$ denotes the node-lane incidence matrix associated with the investigated mine transportation network. $\mathbf{E}_\mathbf{w} \in \mathbf{R}^{|N|}$ is a vector with $|N|-2$ zero components and 2 none-zero components, where non-zero components 1 and -1 denote the origin and destination, respectively. $\mathbf{x}_w^{hm}$ is a vector composed of all lane flow between origin-destination pair w within time interval h, i.e., $\mathbf{x}_w^{hm} = \left(\cdots x_{wa}^{hm} \cdots\right)^{\mathrm{T}}$ for each lane $a \in A$, and $\eta_{w,a}^{hm}$ is an auxiliary variable. The network equilibrium condition within time interval h is defined by [NE-MTF-h]. Constraints (9) guarantee the flow conservation of each mine truck type between origin-destination pair w. Constraints (10) ensure path flow of each mine truck type on lane a is non-negative. Constraints (11) elaborate the relationship between lane flow and path flow, i.e., lane flow is obtained by aggregating path flow. Constraints (12) - (14) are complementary slackness conditions, indicating that all utilized paths have the same and minimal travel cost.

2.2. Operational direction schedules problem with mixed-mine truck flow

In mining operations, fluctuating transportation demands can lead to temporal and spatial imbalances in truck flow, negatively impacting operational efficiency and causing underutilization of road resources. Therefore, it is necessary to develop several different schedules of mine lanes to accommodate the fluctuating transportation demand, i.e., dynamically adjusting the operational directions of mine lanes within each time interval. In general, mine lane direction management problem with mixed-mine truck flow (MLDMP-MTF) should take reconstruction and the scheduling of lane directions into consideration simultaneously. [MLDMP-MTF] is modeled to minimize the total reconstruction cost and total travel cost of CAMTs and CHMTs during the planning time horizon. Several additional notations are defined as follows: Let binary variable y_a represent whether lane a is reconstructed. For each route c, let parameter $\overline{Y}_c$ represent the maximum number of reconstructed lanes on route c. Parameter γ is a conversion coefficient of reconstruction cost to travel cost. With the above notations, [MLDMP-MTF] can be described as following:

[MLDMP-MTF]:

$$\min Z(\mathbf{v}, \mathbf{y}, \boldsymbol{\mu}) = \sum_{a \in A} \sum_{h \in H} \sum_{m \in M} \int_0^{v_a^{hm}} \tilde{t}_a^{hm}(\mathbf{v}, \boldsymbol{\mu}) d\mathbf{v} + \gamma \sum_a \tilde{C}_a(\mathbf{y}) \tag{15}$$

s.t. (10) - (12)

$$0 \leq y_a \leq \overline{Y}_c \qquad \forall a \in c, c \in R \tag{16}$$

$$\mu_a^h + \mu_b^h - y_a - y_b = 0 \qquad \forall a, b \in A, a \neq b, h \in H \tag{17}$$

$$y_a, y_b \in \{0,1\}, \mu_a^h \geq 0 \ \ and \ \ integer \qquad \forall a, b \in A, a \neq b, h \in H \tag{18}$$

Where function $\tilde{C}_a$ denotes the reconstruction cost. Objective function (15) aims to minimize the total operational cost, where the first part corresponds to the total travel cost of CAMTs and CHMTs during the planning time horizon, and the second part implies the total reconstruction cost. Constraints (16) limit the maximum number of reconstructed lanes on route c. Constraints (17) denote the relationship between μ and y. Constraints (18) denote the domains of variables y_a, y_b, and μ_a^h.

3. SOLUTION ALGORITHM

Since [MLDMP-MTF] can be formulated as a DNDP problem, we develop a modified active-set algorithm, which is motivated by Zhang et al[10] to solve the proposed problem. Before introducing the active-set algorithm, we first do some reformulations to the [MLDMP-MTF] as follows: Let parameter σ_a represents the minimal integer that satisfies the function $\overline{Y}_c \le 2^{\sigma_a} - 1$, then we can reformulated the variable y_a as $y_a = \sum_{\varpi=1}^{\sigma_a} y_a^{\varpi} \cdot 2^{\varpi-1}$ for any lane $a \in A$, where index $\varpi \in [1, \sigma_a^h]$. Similarly, let parameter $\sigma_a'^h$ represent the minimal integer which satisfies the function $\overline{Y}_c + \overline{Y}_{c'} \le 2^{\sigma_a'^h} - 1$, then variable μ_a^h can be reformulated as $\mu_a^h = \sum_{\varpi=1}^{\sigma_a'^h} \mu_a^{\varpi h} \cdot 2^{\varpi-1}$ for each lane $a \in A$ within time interval $h \in H$, where index $\varpi \in [1, \sigma_a'^h]$. It is noted that variables y_a^{ϖ} and $\mu_a^{\varpi h}$ are all binary variables. Then, [MLDMP-MTF] can be reformulated as below:

Objective function (15)

s.t. (10) - (12)

$$\sum_{\varpi=1}^{\sigma_a'^h} \mu_a^{\varpi h} \cdot 2^{\varpi-1} + \sum_{\varpi=1}^{\sigma_b'^h} \mu_b^{\varpi h} \cdot 2^{\varpi-1} - \sum_{\varpi=1}^{\sigma_a} y_a^{\varpi} \cdot 2^{\varpi-1} - \sum_{\varpi=1}^{\sigma_b} y_b^{\varpi} \cdot 2^{\varpi-1} = 0 \qquad \forall a,b \in A, a \ne b, h \in H \tag{19}$$

$$y_a^{\varpi} \in \{0,1\} \qquad \forall a \in A, \varpi \in [1, \sigma_a^h] \tag{20}$$

$$\mu_a^{\varpi h} \in \{0,1\} \qquad \forall a \in A, h \in H, \varpi \in [1, \sigma_a'^h] \tag{21}$$

where constraints (19) - (21) are equivalent to constraints (16) - (18). And the integer variables proposed above are all transformed into binary variables. We further convert the constraints (20) and (21) with substituted variables Ω_0, Ω_1, Ω'_{h_0} and Ω'_{h_1} to include the (a,ϖ) let y_a^{ϖ} equal 0, the (a,ϖ) let y_a^{ϖ} equal 1, the (a,h,ϖ) let $\mu_a^{\varpi h}$ equal 0, and the (a,h,ϖ) let $\mu_a^{\varpi h}$ equal 1, respectively. Then, the proposed model can be described as modified mine lane direction management problem with mixed-mine truck flow (MMLDMP-MTF).

When y_a^{ϖ} and $\mu_a^{\varpi h}$ are determined, [MMLDMP-MTF] can be regarded as the mixed-mine truck flow assignment problem which follows the user equilibrium principle. The detailed processes of applied active-set algorithm are similar to those given in Zhang et al[10].

4. NUMERICAL EXAMPLE

In this subsection, the numerical example is conducted on the basis of the Sioux Falls network as shown in Figure 2 to illustrate the proposed model and algorithm. The Sioux Falls network is a medium-scale network consisting of 24 nodes.

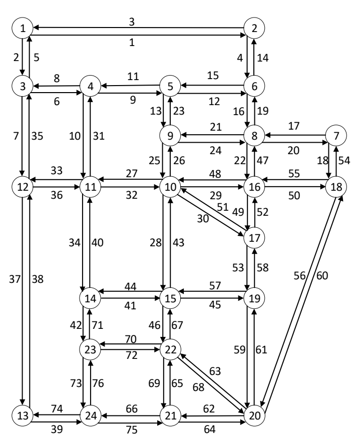
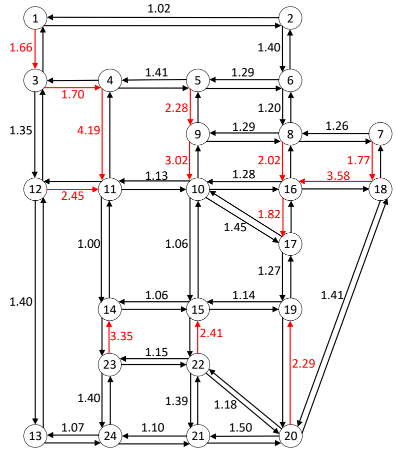
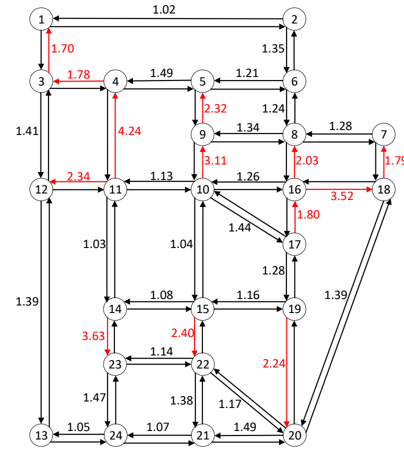


Figure 2. The Sioux Falls network.

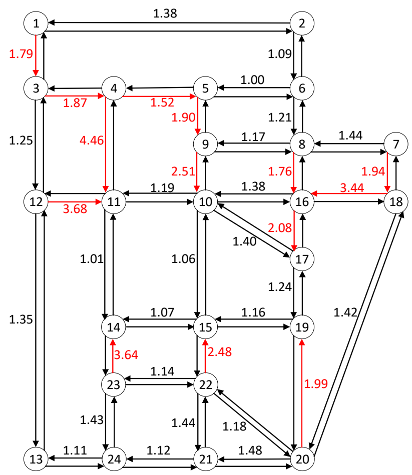
Based on the original data of the Sioux Falls network, we describe the capacity of each lanes in Figure 2.



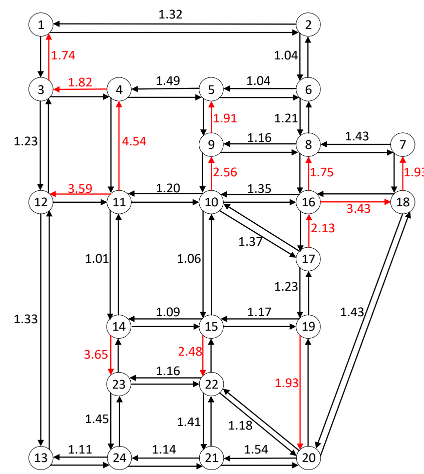
(a) The flow ratios of CAMTs during the daytime



(b) The flow ratios of CAMTs during the nighttime



(c) The flow ratios of CHMTs during the daytime



(d) The flow ratios of CHMTs during the nighttime

Figure 3. The mine truck flow situations without reconstruction of mine lanes.

We define the planning time horizon $|H| = 2$, which includes daytime h_1 and nighttime h_2.During the daytime, the transportation demand is huge, while the transportation demand is small during the nighttime. To reveal the phenomenon of temporal and spatial imbalance of mine truck flow during the daytime and nighttime in the open-pit mines, we do some adjustments to the transportation demand accordingly. For analytical convenience, the reconstruction cost of each lane is assumed to be the same. Then, we formulate the reconstruction cost function $\sum_a \tilde{C}_a(\mathbf{y})$ as a linear function, i.e., $\sum_a \tilde{C}_a(\mathbf{y}) = \sum_a c_a y_a$, where parameter c_a represents the reconstruction cost of each lane. Other default model parameters are assumed as follows: The capacity of CAMTs on each lane is twice that of CHMTs on each lane, i.e., $Q_{a1} = 2Q_{a2}$. With respect to the travel cost $\tilde{t}_a^{hm}\left(v_a^{h1}, v_a^{h2}\right)$ of CAMTs and CHMTs, unit fuel price φ and fuel consumption E_a are set as 1 and 0.1 respectively. Since CAMTs can reduce the fuel cost, the rate of fuel consumption ϑ_1 is 0.85. The rate of fuel consumption ϑ_2 for CHMTs is 1. The VOTs of CAMTs and CHMTs is set as 5 and 10, respectively. Conversion coefficient of reconstruction cost to travel cost γ is set as 1.

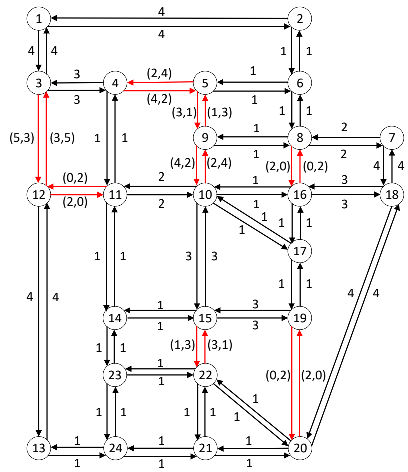


Figure 4. The operational direction schedules of mine lanes.

To validate the impact of reconstructed lanes on the operational performance of mine transportation network, the total travel cost with reconstructed lanes and without reconstructed lanes are compared. Figure 2 shows the mine truck flow situations without reconstructed lanes. It is noted that $v_a^m = \sum_h v_a^{hm}$, where v_a^m denotes the flow of mine truck type m on lane a during the planning time horizon. Although the results of mine truck assignment vary from CAMTs and CHMTs in Figure 3, the directions of heavy traffic are consistent in the scenarios involving CAMTs only and involving CHMTs only, such as lane [1, 3] during the daytime (see Figure 2 (a) and (c)) and lane [4,3] during the nighttime (see Figure 2 (b) and (d)). Besides, the phenomenon of temporal and spatial imbalance of mine truck flow exists in both scenarios. As shown in Figure 2, it can be observed that the temporal and spatial imbalance of mine truck flow exists on many lanes in the mine transportation network, such as lanes [5, 9], [9, 10] and [15, 22]. For instance, the traffic on lane [5, 9] is much heavier than that on lane [9, 5] during the daytime (see Figure 2 (a) and (c)). However, the traffic on lane [9, 5] is heavier than that on lane [5, 9] during the nighttime (see Figure 2 (b) and (d)). Therefore, the reconstruction and operation direction schedules of mine lanes appears reasonable.

Without the consideration of reconstruction cost, the optimal operational direction schedules of mine lanes are shown in Figure 4, where the number of reconstructed mine lanes marked in red is 16. Since lanes [12, 11], [9, 10], [8, 16], [15, 22], [19, 20], and so forth are the main lanes, the reconstructed mine lanes are coincident with commonsense. In particular, one-way traffic is involved in our organization. When implementing the operational direction control technology, lanes [8, 16], [12, 11] and [20, 19] are one-way streets during the daytime, while lanes [16, 8], [11, 12] and [19, 20] are one-way streets during the nighttime. With the reconstruction of mine lanes, the total travel cost of CAMTs and CHMTs reduces by 21.6%. In general, the effect of operational direction schedules of mine lanes is significantly obvious. The different deployment schedules corresponding to the daytime and nighttime improve the overall operational performance of mine transportation network.

5. CONCLUSION

This paper addresses the problem of optimizing lane direction control and scheduling in the context of mixed-mine truck flow, where both CAMTs and CHMTs are involved. Unlike traditional lane management approaches that allow unrestricted lane usage, this study introduces directional restrictions and operational schedules to alleviate congestion and improve road utilization. A bi-level programming model is developed, which simultaneously considers the reconstruction of mine lanes and the scheduling of their operational directions. The upper-level model determines the optimal number of controlled lanes and operational schedules to minimize total operational costs, while the lower-level model captures the behavior of the mixed-mine truck flow, incorporating factors such as fuel consumption and value of time (VOT) into the generalized cost function. To illustrate the proposed model, the numerical example is conducted based on the Sioux Falls network. The results suggest that reconstruction of mine lanes can play a significant role in reducing the total travel cost of mixed-mine truck flow.

This paper can be extended in several directions in the future research. First, the operational direction schedules can be combined with evacuation strategies to improve system resilience in the event of unexpected disruptions. Additionally, this study focuses on a deterministic scenario and does not account for uncertainties. Future research could explore the impact of incorporating uncertain parameters into the lane direction control and scheduling framework.

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