An Effective Heuristic for Stockyard Planning and Machinery Scheduling at a Coal Handling Facility

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Abstract—Coal handling is a complex process involving different correlated and highly dependent operations such as selecting appropriate product types, planning stockpiles, scheduling stacking and reclaiming activities and managing train loads. Planning these operations manually is time consuming and can result in non-optimized schedules as future impact of decisions may not be appropriately considered. This paper addresses the operational scheduling of the continuous coal handling problem with multiple conflicting objectives. As the problem is NP-hard in nature, an effective heuristic is presented for planning stockpiles and scheduling resources to minimize delays in production and the coal age in the stockyard. A model of stockyard operations within a coal mine is described and the problem is formulated as a Bi-Objective Optimization Problem (BOOP). The algorithm efficacy is demonstrated on different real-life scenarios. Computational results show that the solution algorithm is effective and the coal throughput is substantially impacted by the conflicting objectives. Together, the model and the proposed heuristic, can act as a decision support system for the stockyard planner to explore the effects of alternative decisions, such as balancing age and volume of stockpiles, and minimizing conflicts due to stacker and reclaimer movements.

I. INTRODUCTION

In the past 10 years, Australia has become the world’s leading coal exporter [1]. There is an urgent need to improve the current processes to increase the throughput and meet the high demand. Additionally, there are many challenges facing stockyard planners, either at the mine or the shipyard, in scheduling and resolving conflicts between stackers and reclaimers and selecting the appropriate stockpiles for stacking and reclaiming operations. Coal rehandling is time consuming, affecting the coal quality and adding additional cost in terms of operation and equipment. At the same time, a stockyard is required to have sufficient amounts of coal and diversity of product types available with a moderate balance of volume distribution on the stockpiles in order to avoid any impacts on reclaiming. Also, the age of coal in the stockyard is crucial as customers demand to have fresh coal that was not stacked for long periods.

Scheduling is a major challenge faced by stockyard planners. The above mentioned factors and their inter-dependencies add an enormous level of complexity to planning production and scheduling resources. It requires a group of experienced personnel to create an efficient and robust schedule for such a complex and time consuming process. Moreover, the nature of uncertainties and unforeseen changes, such as machinery break down and train delays, make it hard to reschedule on the spot and still produce optimized schedules. Automating this process is crucial to remove part of the operational costs, produce effective schedules and avoid uncertainties delaying the production; hence, reducing the overall cost of coal production.

Research addressing challenges in the coal supply chain vary depending on many aspects, including the chain end-to-end optimization model (i.e., mine-to-factory, mine-to-port), the stockyard layout and the machinery movement constraints, the operational site (i.e., mine, port, or factory), the model of the rail system and the objectives to be satisfied when planning and scheduling. Borland et al. [2] developed a shipyard model to represent decisions and constraints typically applied at a planning stage of about 4 to 6 weeks in advance for allocating stockpiles to vessels. The key decisions are where on the stockyard to place each stockpile for a vessel, when to start building the stockpile, when to bring the vessel to berth, and when to start reclaiming and loading each stockpile for the vessel. A greedy solution approach is proposed with the goal of minimizing vessel sailing delays, and maximizing throughput of the system. In a recent work, Borland et al. [3], combined the greedy approach proposed earlier with enumeration and integer programming to investigate the benefits of capacity expansion investments on throughput levels.

Abdekhoodaei et al. [4] addressed the integration of operational or demand driven train timetabling and stockyard management at shipyard port terminal. They proposed a greedy heuristic to solve the problem with more focus on train scheduling than stockyard management. Conradie et al. [5] presented a simulated annealing approach to optimize the supply of coal to a factory producing liquid fuel products. They focused on developing robust schedules that can accommodate fluctuations in the product demand observed at the factory. One of their objectives was to meet the blend requirements to produce liquid gas of certain standard which they achieved by minimizing ash and other fine content.

Binkowski and McCarragher [6] modeled the mining stockyard using queuing theory to address issues, such as the optimal number and size of stockpiles to maintain in the stockyard, and the train arrival rate, in order to minimize vessel delays and increase the overall throughput.
Ayu and Hall [7] made use of queuing theory to find the optimal availability rate of ore in the stockyard along with the optimized capacity and number of stockpiles in the stockyard.

On the other hand, Sandeman et al. [8] presented two different case studies in mining describing the benefits of integrating optimization formulations within simulation models. They compared offline and online simulations of the optimization models to produce a long term plan for managing the movement of coal with different stockyards from coal to port. They showed the ability to examine the trade-offs between different options for capital expenditure, as well as assessing alternative operating practices, including maintenance options, through quantification of potential performance.

Similar challenges have been addressed but in different contexts and domains. Hu and Yao [9] addressed only the scheduling of machinery at a raw material yard. They used a genetic algorithm to find an optimal operation sequence on each stacker-reclaimer in order to minimize the task completion time. In the domain of precast concrete products, Marasani et al. [10] developed a simulation model embedding genetic algorithms to help identify the stockyard layouts and manage the stockyard space for efficient storage and retrieval standard concrete products. Their key objective was to reduce the throughput time of the process. Zhen and Chang [11] addressed the problem of berth allocation for container terminals. They developed a bi-objective model for minimizing the cost and maximizing the robustness of the schedule. The proposed model incorporates a degree of anticipation of uncertainty (e.g., vessels arrival time and operation time) during the schedules execution.

In this paper, we address a coal handling facility. The facility has two streams of coal flowing from the wash plant with one stacker associated with each flow. Trains arrive to the load out point and are loaded using two reclaimers in a window of 2 hours duration. The movement of each stacker or reclaimer is constrained with the location of the other stacker or reclaimer. Selecting the appropriate stockpile for stacking a coal type is crucial to ensure diversity of products in the stockyard, maintain the lowest age of coal and minimize the conflicts arising from machinery movements. Additionally, stockpiles volumes should be balanced to ensure availability of reasonable ratios for the two reclaimers to meet the two hours train loading window. The problem is formulated as Bi-Objective Optimization Problem (BOOP) with the objectives of minimizing the delays introduced on the continuous flow of coal (i.e., coal production) from the plant due to stocker unavailability, while moving between stockpiles, and minimizing the overall age of coal in the stockyard. In other words, it is required to plan and manage the selection of stockpiles and schedule the stacking and the reclaiming activities to meet the highest possible coal throughput.

The rest of this paper is organized as follows. Section II describes the various phases of the coal handling process and Section III presents the stockyard layout. In Section IV, we present the formulation of the problem and the proposed solution approach in Section V. The computation results are presented in Sections VI. Finally, we conclude and present the future directions in Section VII.

II. THE COAL HANDLING PROCESS

Newman et al. [12] describes the mine extraction process encompassing five stages, namely prospecting, exploration, development, exploitation and reclamation. In the first stage, geologists determine the quality of mineral deposits. In the second stage, geologists use several techniques to calculate the quantity and develop a feasibility report. The third stage is the preparation and planning of engineering designs, determining infrastructure capital, and estimation of production capacity. Coal is being extracted, in the fourth stage and moved by truck or conveyor either to stockpiles for later processing, or sent directly for processing at a plant or dump. Final stage is environmental restoration.

The coal handling process addressed in this paper consists of three phases. Firstly, miners are given the schedule for coal extraction to meet the demand of the shipping port. Secondly, the extracted coal is processed in the plant and pushed out on a single conveyor or on both conveyors to be stacked by the stackers onto the appropriate stockpiles. In the third and final phase, coal is reclaimed from the stockpiles and loaded onto trains using the two available reclaimers either equally or with different ratios depending on the volumes and availability of coal in the stockyard. The model presented in this paper will deal with the second and third phases i.e., scheduling of stackers and reclaimers and managing the selection of the appropriate stockpiles for stacking and reclaiming.

From the stockyard point of view, the flow of coal occurs simultaneously inward from the plant to the stockyard and outward from the stockyard to the trains. This produces conflicts as both stackers and reclaimers are required to move concurrently to fulfill the required stacking and reclaiming operations; however, there are several constraints on their locations relative to each other and relative to accessing the stockpiles. The stockyard layout, the number of stockpiles and the length of each stockpile are fixed. In our model, a campaign refers to a specific coal type or a pair of coal types either bypassed or processed through the plant. A campaign consists of several activities depending on the stacker and the stockpile. For example, a campaign consists of one activity if it is been handled by one stacker and stacked onto one stockpile, while another campaign consists of four activities if handled by either one or more stackers and stacked onto four stockpiles.

Delays in the coal production can be caused by stacker relocation from one stockpile to another or a stacker giving way to a reclaimer. These delays may result in plant stoppages, therefore, it is required to create a schedule with a minimum tolerance for interrupting the production facility due to the relocation of stackers and reclaimers. Additionally, reclaimers should be ready beforehand on the stockpiles designated for reclaiming in order to avoid any delays in train departures and to maintain the 2 hours duration for loading a train. Both reclaimers are required to load the train within 2 hours.
III. THE STOCKYARD LAYOUT

Figure 1, presents the stockyard layout consisting of the coal processing plant, the conveyors, stacker-1, stacker-2, reclaimer-A, reclaimer-B and Train Load Out (TLO) point. There is a total of 14 stockpiles in the stockyard. These stockpiles serve as buffers for the coal before it is loaded onto trains and are also used for blending. The stockyard is served by two stackers and two reclaimers. Conveyor-A1 and conveyor-B1 run into stacker-1 and stacker-2 respectively, whereas conveyor-A2 and conveyor-B2 run out of reclaimer-A and reclaimer-B respectively. The layout has been designed in such a way that stockpiles are divided into two pads comprising of seven stockpiles each, located parallel to each other. Stackers run in between the two pads and can stack on both pads, whereas, each reclaimer is assigned a single pad. Stockpile toes/length can be altered and two or more stockpiles can be merged, in order to increase or decrease the capacity of a stockpile; however, our model considers only the fixed layout presented above. The following summarizes the constraints on the locations and the movements of the stackers and the reclaimers.

- Stacker-1 cannot stack onto stockpiles A7 and B7, while stacker-2 cannot stack onto stockpiles A1 and B1.
- Stacker-1 cannot pass/overtake stacker-2. The same applies for stacker-1.
- A stacker cannot stack to a stockpile being reclaimed and vice versa.

IV. THE BI-OBJECTIVE MODEL

The developed model simulates the formerly described coal handling process. The coal processing plan is designed a week ahead of the production. The planner examines the stockpiles and attempts to construct a feasible schedule for the stackers’ activities to handle the flow of coal described in the plan. Also, the planner selects the appropriate stockpiles to stack each type of coal and the specified volume. Additionally, the stockyard planner creates a schedule for the reclaimers’ activities to fulfill the trains schedule based on the expected status of the stockpiles and the existing volumes. The two main objectives the planner is working to minimize are the delay introduced on the continues flow of coal from the plan due to machinery movements and changing stockpiles; and the age of coal on each stockpile. The model can be formulated as follows:

**Parameter Sets**

- $C$: Set of campaigns
- $S$: Set of stockpiles
- $K$: Set of stackers
- $R$: Set of reclaimers
- $T$: Set of trains
- $P$: Set of pads
- $H(s, p)$: Set of positions of stockpiles on pad $p$

**Parameters**

- $t_{start}^c$: Planned start time for campaign $c$, where $c \in C$
- $p_c$: Coal type for campaign $c$
- $v_c$: Volume for campaign $c$
- $t_{arr}^a$: Estimated arrival time for train $a$, where $a \in T$
- $v_a$: Volume of train $a$
- $len_p$: Length of pad $p$, where $p \in P$
- $len_s$: Length of stockpile $s$ on the pad, where $s \in S$
- $v_s$: Volume of stockpile $s$
- $p_s$: Coal type of stockpile $s$
- $cap_s$: Capacity of stockpile $s$
- $pos_k$: Position of stacker $k$ on pad $p$
- $pos_r$: Position of reclaimer $r$ on pad $p$

**Decisions**

- $t_{act}^c$: Actual start time for campaign $c$
- $t_{load}^a$: Loading start time for train $a$
- $v_c^s$: Volume of campaign $c$ assigned to stockpile $s$
- $v_a^r$: Volume loaded by reclaimer $r$ for train $a$

**Implied Sets**

- $S(c)$: Set of stockpiles for campaign $c$
- $S(a)$: Set of stockpiles for train $a$
- $K(c)$: Set of stackers for campaign $c$
- $R(a)$: Set of reclaimers for train $a$
**Implied Decisions**

- $t_{a}^{dep}$: Estimated departure time for train $a$
- $age_s$: Age in days of stockpile $s$

**Objectives**

- Minimize the total delay in campaigns:
  \[
  \sum_{c \in C} (t_{c}^{act} - t_{c}^{start}) + \sum_{k \in k} D_{s}^{k}
  \]
  where $D_{s}^{k}$ is time duration required by stacker $k$ to move from stockpile $s$ to stockpile $\hat{s}$ for campaign $c$.
- Minimize the average age of stockpiles:
  \[
  \frac{1}{|S|} \sum_{s \in S} age_s
  \]

**Constraints**

- A campaign cannot start before its designated start time:
  \[
  t_{c}^{act} \geq t_{c}^{start}, \quad \forall c \in C
  \]
- A campaign must be stacked onto a stockpile with the same coal type:
  \[
  p_s = p_c, \quad \exists c \in C \text{ and } \exists s \in S
  \]
- A stockpile cannot accommodate coal more than its maximum capacity:
  \[
  \sum s_{c}^{u} \leq cap_s, \quad \forall c \in C
  \]
- A train cannot be loaded before its estimated arrival time:
  \[
  t_{a}^{load} \geq t_{a}^{arr}, \quad \forall a \in T
  \]
- A stacker/reclaimer cannot stack/reclaim on/from a stockpile having a reclamer/stacker:
  \[
  pos_{c}^{k} \neq pos_{r}^{p}, \quad \forall p \in P, \forall k \in K, \forall r \in R
  \]
- Stacker-1 cannot pass or overtake stacker-2:
  \[
  pos_{c}^{1} \leq pos_{c}^{2}, \quad \forall p \in P
  \]

**V. Solution Approach**

This section describes the main steps of the proposed heuristic algorithm. Currently, the process followed by the stockyard planner bases all decisions on the current state and does not incorporate any global optimization for the selection of the stackers and reclaimers and the stockpiles. Furthermore, manually designing the plan for a whole week creates many unforeseen conflicts which requires extra efforts in replanning to resolve them. The proposed algorithm schedules campaigns and trains one at a time in a non-decreasing order of the campaign’s volume and the train’s estimated arrival time. This involves for each campaign and train the following steps:

- For each campaign $c$ in the order in which they are planned to start, first find the feasible set of stockpiles $S(c)$ with matching coal type to the campaign. Second, construct the stackers set $K(c)$. In this case, set $K(c)$ can have one or both stackers depending on the stacker position and the accessibility of the stockpiles in $S(c)$ by that stacker. A tie-breaking rule is employed to choose the minimum on objective (1) if no $s$ from $S(c)$ and $k$ from $K(c)$ to minimize objectives (1) and (2). Also, in the case that the campaign’s volume is more than the space available on the current selected stockpile, the stackpile is filled to capacity and the same procedure is repeated for the remaining portion of the campaign’s volume.
- For each train $a$ in the order in which they are estimated to arrive, first find the pair of stockpiles on both pads that have a matching coal type and are the oldest in age. This is always to ensure that the oldest stockpiles are reclaimed to base to fulfill minimizing objective (2). Second, calculate the ratio of volumes to be reclaimed. In most cases, an equal ratio of 50% will ensure that the train can be loaded in around 1 hour duration; however, the ratios can reach up to 70% and 30% and still the train can be loaded in a 2 hours duration. In case there is not enough coal in the stockyard to load the train, or the coal types are not matching on both pads, then this train is canceled. Obviously, this situation occurs rarely as the stockyard is ensured to have enough quantity and diversity of coal types.

Algorithm 1, shows the main steps of scheduling campaigns and trains. It is worth noting that the algorithm represents the pseudo-code in general and is meant to give insight into the logic of the main procedure. It is not necessarily representative of the actual implementation as it leaves out many details and complexities. For example, when finding the feasible stockpiles set $S(c)$ for campaign $c$, it is ensured to eliminate all stockpiles having coal type different than the campaign’s coal type as mixing different coal types on a stockpile is unacceptable.

**VI. Computational Results**

This section reports on a computational study conducted to evaluate the performance of the proposed heuristic and to assess the improvements incorporated in automating the process of scheduling the stackers and the reclaimers as well as planning the coal in the stockyard. In the experiments of this study, we tested the algorithm using 10 real-life scenarios, each has a planning period of 1 week with a time unit of 1 hour. The scenario consists of the plan produced by the coal processing plant for the campaigns to run during the week, the volume of each campaign, the coal product, and the conveyor on which the campaign will flow out from the plant. The volumes of campaigns in the scenarios increases gradually from one scenario to the next with the last four scenarios having the highest volumes. Three different fill levels for the stockyard, low, medium and high are used with each scenario to represent the initial volume of coal in each stockpile.

First, we run the algorithm for the set of campaigns with the same order provided by the plant and compute both objectives: the total delay and the total age. It is worth to note that the motivation of the stockyard planner is to construct a schedule
In most cases, better measures are obtained for both the total delay and the average age. In some cases, due to the conflicting nature of the objectives, enhancing one objective affects or worsens the other. Figures 2 to 5, graphically show the results in Table I. An important note is the high degree of variability from one scenario to another and the high dependability on the state of the stockyard. Randomization reduced the variability by taking the best of a number of random runs giving better results in terms of the total delay with an average improvement of 66.63% and an average decline of 19.83% in terms of the average age. This shows that the two objectives are conflicting; however, this is not necessary as in some scenarios the one objective is minimized while maintaining the same average age.

VII. Conclusions and Future Work

The model presented in this paper demonstrates the ability to automate the stockyard planning process and to schedule the machinery operations. The model captures the constraints imposed by the stockyard layout on the movements and locations of stackers and reclaimers. The proposed heuristic is capable of meeting the main objectives for both the processing plant and the stockyard planner with the ability to produce better production plans. Both, the model and the heuristic, can

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**Algorithm 1** Campaign and Train Scheduling

order campaigns in $C$ by $t^\text{start}_c$

order trains in $T$ by $t^\text{arr}_a$

while $c \in C$ and $a \in T$ do

if $t^\text{start}_c < t^\text{arr}_a$ then

for $s \in S$ do

find the feasible stockpiles set $S(c)$ for $c$

end for

for $k \in K$ do

construct the feasible stackers set $K(c)$

end for

choose $s$ from $S(c)$ and $k$ from $K(c)$ to minimize objectives (1) and (2)

calculate $t^\text{act}_a$ for $c$

if $v_a > cap_s - v_s$ then

assign volume $cap_s - v_s$ to stockpile $s$

update $v_c$

update $t^\text{start}_c$

else

assign volume $v_c$ to stockpile $s$

update $t^\text{act}_a$

goto next $c$

end if

else

for $s \in S$ do

find the feasible stockpiles set $S(a)$ for $a$

end for

for $s \in S(a)$ do

find the pair of oldest $s$ in $S(a)$ for each $r$

calculate volume ratios $v_{s1}$ and $v_{s2}$

if $v_a < v_{s1} + v_{s2}$ then

update $t^\text{load}_a$

break

end if

end for

if train could not be scheduled then

cancel train $a$

else

goto next $a$

end if

end if

end while

---

**Table I** Results of computational study showing the total delay (in hours) and the average age (in days) against the minimum obtained when randomizing the order of the campaigns

<table>
<thead>
<tr>
<th>Stockyard Level</th>
<th>Scenario</th>
<th>Total Delay (hours)</th>
<th>Average Age (days)</th>
<th>Minimum Total Delay (hours)</th>
<th>Minimum Average Age (days)</th>
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act as a prototype decision support system for the stockyard planner to explore different stockyard management strategies. There is potential to improve the algorithm by incorporating a meta heuristic search approach to help obtain better results for the required objectives. In future work, further investigation will be carried out to ensure that the decision support tool is fully reliable for managing stockpiles and scheduling resources during the planning process of coal production. Additionally, the model will be extended to incorporate stockpiles location decisions and trains related objectives.

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REFERENCES