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REVIEW

A Review of Current Scheduling and Design Practices in the Powder River Basin

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Abstract

Area mining is a surface mining method that allows for efficient mining and contemporaneous reclamation of tabular or bedded deposits, e.g., coal. Mine planning methods for area mines differ from those of open pit metal mines. Area mines in the Powder River Basin (PRB) use various processes for mine planning at both the strategic and tactical stages. With the ever changing commodity markets, it is becoming increasingly important for mine operators to be able to react quickly to the changing business environment. Tools that allow for the development and rapid comparison of production schedule scenarios are key to ensuring agile mine operations. A survey of mine engineers responsible for mine design and production scheduling at coal operations provides clarity on the current mine design and production scheduling processes in the PRB, as well as a discussion on potential solutions to upcoming challenges. In this article, we describe various mine planning processes used by the coal producers in the Powder River Basin. The survey identifies a clear gap in the ability to create comprehensive schedules associated with limited tools and lack of engineering labor needed to frequently conduct the mine design and scheduling process.

Keywords Coal mining · Mine planning · Mine design

1 Introduction

The Powder River Basin (PRB), located in the western United States, is a coal mining region that has evolved throughout the half century since the first large-scale mine began in the 1970s, as shown in Fig. 2. Challenges related to commodity pricing, high inflationary periods and, more recently, low demand, associated with power producers switching from coal to natural gas or renewable energy sources, have impacted the industry [1–3]. While production has decreased in recent years, Powder River Basin coal continues to provide a low-cost energy source to power generation facilities across the USA [2]. In addition to domestic consumption, a small percentage of PRB coal is exported to Asia. In 2018, 4% of coal production from the PRB was exported. Thinning margins have led companies operating in the PRB to evolve and apply various technologies, equipment, and mining methods in order to remain profitable [4, 5]. These challenges have operators seeking opportunities to lower costs via emerging technologies and reevaluating the mine planning and production scheduling processes.

Area mining refers to a surface mining method used to mine tabular or bedded deposits in which overburden, i.e., waste, and target materials, i.e., desired commodity, are excavated and the land is contemporaneously reclaimed. This method is often used to extract near surface coal deposits, but is also used with other materials such as phosphate, bauxite, tar sands, manganese, and some industrial minerals [6]. Area mines typically operate at depths of up to 150 m (492 ft), but depending on the deposit type and geometry, potential exists to extend this mining method to depths of more than 300 m (984 ft) [6]. Figure 1 illustrates commonly conducted activities at an area mine spanning from ground preparation to active mining and reclamation. The area mining process is described as, (i) topsoil material is removed and either stockpiled or placed on newly reclaimed land, (ii) truck and shovel fleets remove prestrip material, i.e., material that lies above the maximum dragline operating height, (iii) draglines

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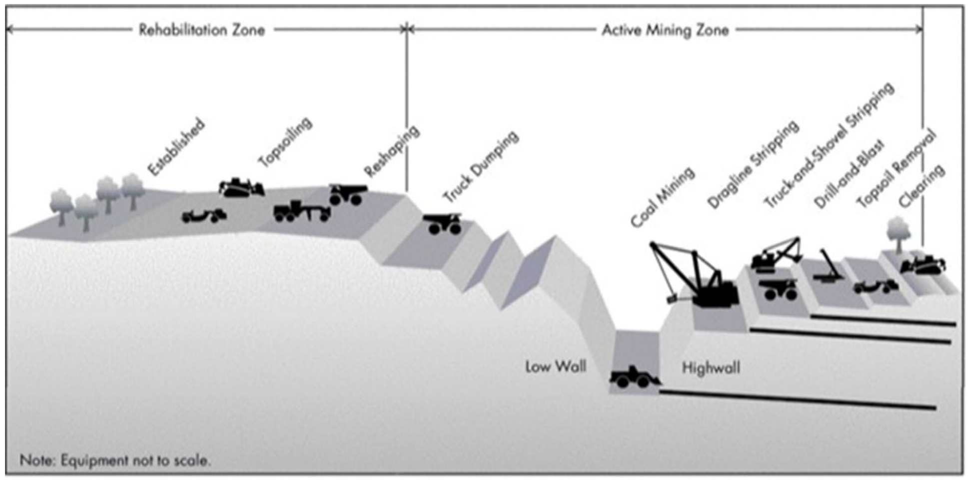


Fig. 1 Area mine life-cycle beginning with initial topsoil removal and ending with final reclamation [6]

or truck and shovel fleets uncover coal and place the overburden in a previously mined area creating spoil piles or waste dumps, respectively, (iv) the coal is extracted using trucks and loaders, (v) the spoil piles or waste dumps are contoured and reshaped to mimic the original or approved topography, and (vi) topsoil is placed on the reclaimed land and native flora are planted in the area [7, 8].

Area mining operations utilize unit operations, i.e., drilling, blasting, loading and hauling, in a continuous manner that expedites reclamation, unlike other surface mining methods. While mining strategies can differ across mines, equipment that exploits the economies of scale, e.g., high-capacity draglines, cable shovels, are often employed to reduce production costs on a per unit basis [2, 9]. *Area mining*, sometimes referred to as strip mining or open-cast mining, is employed throughout the Powder River Basin in the USA and Australia's Bowen Basin [6–8, 10]. This paper focuses on describing and documenting the current mine planning and scheduling techniques employed in the surface coal mines of the Powder River Basin.

While commercial mining in the region began in the 1920s, large-scale, non-captive mining in the Powder River Basin did not commence until the 1970s with opening of the Belle Ayr Mine in 1972 [1, 2, 11]. A non-captive mine is an operation that sells coal to various power generating facilities [12]. During this time of expansion, the majority of the mines were owned and operated by oil companies looking to diversify their holdings, while other motivations included the environmental movement and the energy crisis in the 1970s [1]. Initial mine development was completed in conjunction with long-term coal supply agreements with power plants specifically designed to burn coal from the Powder River Basin [1]. Amendments made to the Clean Air Act in 1990 led to further expansion of production as utilities looked to switch from higher sulfur coals produced in the eastern United States to the low sulfur coals of the Powder River Basin in the western United States [2]. Current operations in the Powder River Basin are a mixture of captive mines, i.e., mine-to-mouth power generation facilities, such as Wyodak, Coalstrip (Rosebud), Absaloka, and Dry Fork mines and non-captive mines such as Antelope, Belle Ayr, Black Thunder, Buckskin, Caballo, Coal Creek, Cordero Rojo, Eagle Butte, North Antelope Rochelle, Rawhide, and Spring Creek mines [13]. Mine-to-mouth or captive mines refer to mines that produce coal for an adjacent power generating facility [14].

Much of the coal produced in the Powder River Basin is sourced from Campbell and Converse counties in Wyoming which is considered the Southern Powder River Basin. The Northern Powder River Basin consists of mining operations located in Montana, which provided less than 10% of the total production from the Powder River Basin in 2021 [15]. Figure 2 shows the extent of the Powder River Basin highlighted and cross-hatched.

Geology in the PRB differs from other US coal basins. PRB coal is relatively shallow and flat lying, especially in the eastern and central portions of the PRB, where many of the active mining operations are located. The coal seams in the PRB are between 15 and 33.5 m (49 and 110 ft) thick with some regions having seam thicknesses of up to 61 m (200 ft). Coal depths in the active mining region vary from 0 to approximately 167 m (548 ft) with stripping ratios varying from less than 1:1 to 4:1 at reserves bordering current operations [17]. Maximum coal depth along the western side of the basin approaches nearly 500 m (1,640 ft) although no active mining operations are extracting coal at this depth. Comparatively, coal extracted in the Northern and Central Appalachia coal basins average approximately 1 m (3 feet) thick and with depths of greater than 330 m (1,083 feet) [18]. The thick coal seams found in the PRB, combined with low strip ratios, i.e., ratio of waste required to uncover a ton of coal, have helped to create mining operations with high efficiencies, i.e., higher production per man hour, and low unit costs, i.e., cost per ton or cost per cubic yard, by allowing the use of bulk mining methods to generate economies of

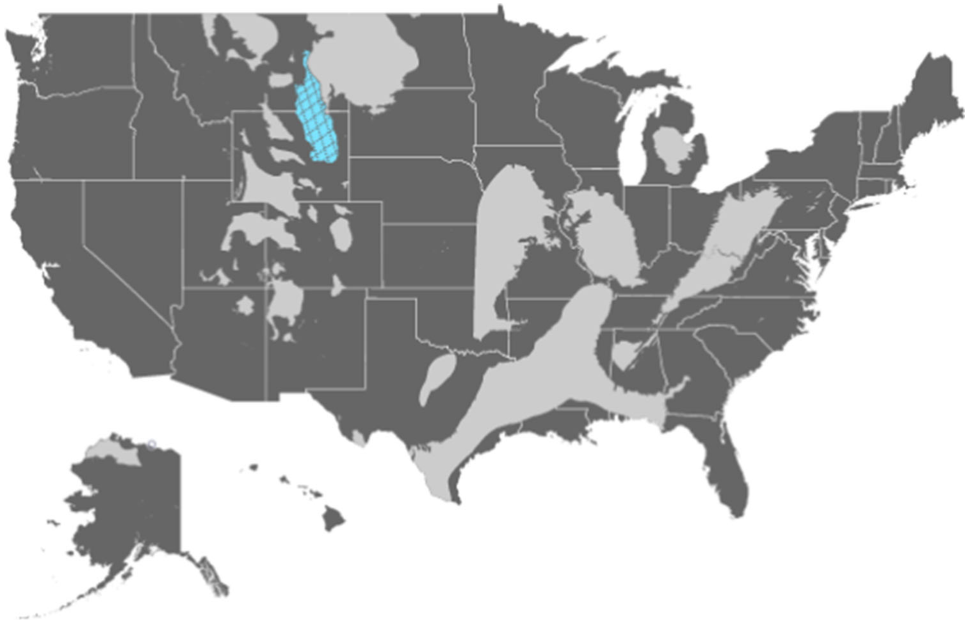


Fig. 2 US coal basins with Powder River Basin mining region highlighted and hatched Adapted from: [16]

scale [2]. Mines in the PRB may mine a single seam or multiple seams [19]. This unique geology facilitates the use of very large mining equipment, e.g., draglines, throughout the PRB [2]. At North Antelope Rochelle Mine, dragline capacity ranges from 21 million cubic yards per year to 36 million cubic yards per year on four draglines with bucket capacities ranging from 72 cubic yards to 135 cubic yards [20]. Black Thunder Mine employs six draglines with bucket capacities ranging from 164 to 169 cubic yards [21].

1.1 Evolving Mining Practices in the Powder River Basin

Mining practices in the Powder River Basin have evolved from truck and shovel fleets that were employed by the first large-scale mining operations in the 1970s to multipit operations using a variety of mining methods in present day. Changes to mining practices in the Powder River Basin have been driven by a need to lower costs associated with increasing strip ratios, competition from eastern US coal and natural gas producers, and environmental pressures from the green energy movement. To overcome these challenges, mines focused on ways to reduce costs and increase mining efficiencies, often through infusions of capital in the form of new, larger equipment.

Mining practices in the 1970s focused on the use of truck and shovel fleets for excavation of both overburden and coal. Starting in the 1980s, many mines in the PRB transitioned to using a combination of cast blasting, dragline, and truck/shovel excavation methods. Necessitated by increased competitive pressures, mines began to embrace new equipment technology to become more efficient and profitable [5]. Cast blasting was a key component of the transition to dragline operations and was tested in the mid-to-late 1980s and early 1990s in the Powder River Basin [5]. This blasting method, described in more detail in Section 2, is used to “throw” overburden material in a previously mined void using explosives rather than loading and haulage equipment. Prior to the evaluation of cast blasting in the PRB, this method was developed and tested in South Africa and Alabama, USA [5].

Between 1972 and 1982, 10 mines opened in the PRB that utilized truck and shovel fleets for both coal and overburden removal [1, 5]. Coal Creek and North Antelope mines, opening in 1983 and 1984, respectively, were both developed as dragline operations while Cordero, Caballo Rojo, Antelope, and Black Thunder mines all transitioned from truck and shovel to dragline operations in the 1980s [5, 22]. Many of these transitions were driven by economics; as strip ratios increased, margins decreased, and coal quality specifications became increasingly restrictive requiring the lower cost dragline production methods and higher production rates [1]. During the 1980s, when many of these mines were transitioning from truck and shovel to draglines for overburden removal, the cost of excavation with a dragline was half of that of a truck and shovel fleet [22]. Although an important component of the decision to implement draglines, the costs associated with operation must be weighed against flexibility, reclamation schedules, coal recovery, permitting requirements, workforce acceptance, and coal quality blending constraints [22]. Management at operations continuing to use truck and shovel fleets have cited concerns with spoil stability and the higher capital expenditure required to transition to a dragline operation as reasoning for maintaining current


(a) (b)

Fig. 3 (a) Truck and shovel excavating overburden Source: Photo by Amy McBrayer, (b) Dragline excavating overburden above truck and shovel loading Source: Photo courtesy of Wyoming Mining Association [24, 25]

equipment fleets [23]. Figure 3(a) shows a shovel excavating overburden and loading a truck and (b) shows a truck and shovel at the coal face with a dragline excavating overburden in the background.

During the 1980s and 1990s, mine consolidation occurred throughout the PRB as larger, more productive mines were required to maintain competitive operations with midwestern and eastern US coal producers as well as within the PRB itself in a period of low coal pricing [1, 26]. Transitioning from 20 active mines in 1993 to 16 active mines in 1997 and finally to 15 mines in 2022, producers consolidated operations to focus on large, productive mining complexes with multiple pits rather than numerous single pit mines [12, 15, 26]. Examples of this transition include the combination of the North Antelope mine with the Rochelle mine and integration of the School Creek Mine with the North Antelope Rochelle mining complex, Arch's acquisition of Jacobs Ranch and integration into their Black Thunder Mine, and the Cordero Rojo Complex, a combination of the Cordero and Caballo Rojo mines [27]. This, combined with increases in equipment size and efficiencies, has assisted with mines remaining economically viable [11].

The evolution of mining practices, coupled with advanced mining technologies and a unique geology, has allowed labor productivity in the PRB to be 9 times greater, on average, than other US coal producers, making the PRB the most productive coal region in the US [2, 28]. Combining these characteristics with the implementation of advanced mine planning and design software tools has shown an increase in the accuracy and efficiency of mines operating in the PRB [5]. In addition, declining transportation rates improved the competitiveness of PRB coal. Between 2008 and 2020, rail transportation costs decreased by 8.5% [29]. Transportation costs can account for up to 50% of the total cost of coal to the utility, therefore, the decrease in transportation costs benefits both the producer and consumer [2].

Mine engineers and production planners are tasked with creating and implementing mine plans and production schedules [5]. Mining companies within the PRB utilize a variety of mine planning and scheduling techniques to meet the demands of customers despite varying commodity prices and thinning margins. Current design and scheduling processes use technology such as 2- and 3-dimensional mine design software and heuristic-based scheduling software or spreadsheet-based scheduling to generate mine schedules, but are not equivalent to those scheduling software packages available to open pit and underground mine planners. Schedules are often only generated for a few scenarios with slight changes to input variables such as coal demand or coal price.

1.2 Impacts of the Mining Industry in the Powder River Basin

Mining in the Powder River Basin provides significant impacts to the state of Wyoming, local communities, and the greater United States. Mines in the Powder River Basin account for 43% of the coal produced in the USA and nearly 50% of the coal produced for use in power generation [15, 30, 31]. Much of the coal mined in the Powder River Basin is owned by the U.S. Federal Government [2]. Therefore, instead of private individuals receiving payment for the extraction of the coal, the general populace of the USA receives the benefit of royalties [12].

A 2013 study indicated that the net social benefit of generating power with PRB coal was $80 billion per year [2]. This study did not include the benefits generated by royalties, taxes, and direct and indirect employment. In 2019, the Federal Coal Leasing Program generated $500M in both state and federal taxes and royalties and also had significant economic impacts associated with direct and indirect employment [32]. While this statistic covers all coal produced under the Federal Coal Leasing Program, 85% of coal produced under this program is from the Powder River Basin [33]. Direct impacts of US coal production in 2020 were $26 billion in sales and $10 billion in wages according to a 2020 National Mining Association analysis [34]. A 2022 study indicates the direct and indirect impacts of US coal production, including both thermal and metallurgical coal, to be $43.5 billion in 2021. In addition, coal production generated $2.3 billion in state

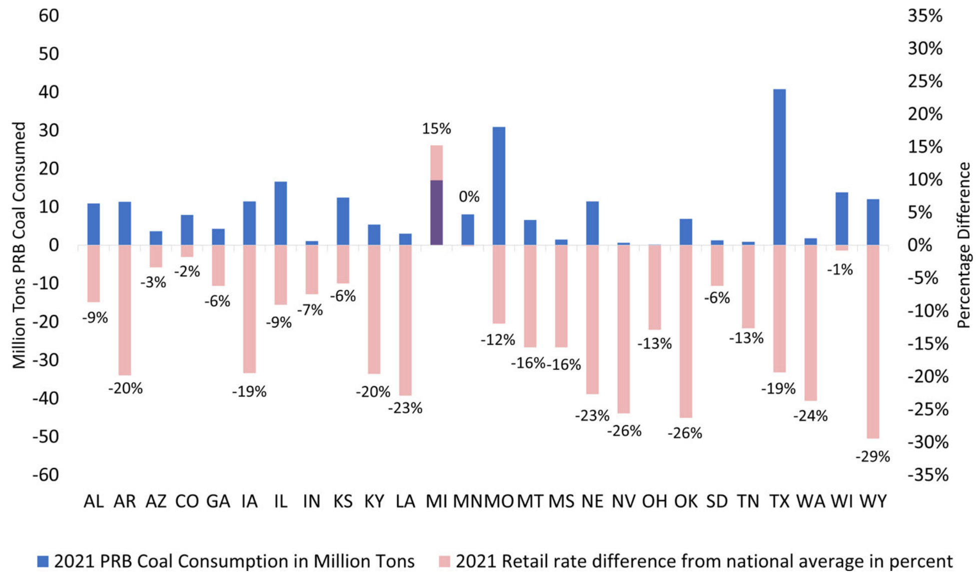


Fig. 4 Percentage cost variance between US average electricity costs and state average electricity costs in states generating electricity from PRB coal in 2021 [36, 37]. The figure provides the coal transported in millions of tons from the PRB to US states and the percentage difference in electricity costs in each state compared to the US average in 2021

and local tax revenues. The same study determines the combined economic impacts of US coal production and power generation from thermal coal to be $261 billion [35].

In addition to the taxes, royalties, and direct impacts of coal sales and wages, mining in the PRB has contributed to a reduction in electricity prices nationwide [2]. These reductions in electricity costs have assisted with spurring economic growth and electrification. Figure 4 shows the consumption of PRB coal in 2021 and the electric rate differences of states consuming PRB coal compared to the national average electric rates. All states consuming PRB coal in 2021 had electricity costs equal or lower to the national average with the exception of Michigan. Figure 5 shows the overall decrease in residential electric rates through 2004 when PRB coal consumption was increasing. Beginning in 2006, the percentage of coal used for electric generation in the USA decreased. The energy producers began switching to natural gas fueled power plants resulting in reduced demand for PRB coal [2]. A significant impact on the cost of electricity can still be seen in states such as Wyoming that generates approximately 73% of their electricity from PRB coal and enjoys a 29% lower cost of electricity than the national average [36]. A reduction in the cost of electricity in many of these regions has led to economic development in the form of manufacturing and other energy intensive industrial applications [2].

Impacts of PRB coal production extended far beyond the economic impacts previously discussed. As production and transportation costs decreased, the cost of PRB coal on a heating value basis, measured in British Thermal Units (BTU or kjoules), decreased to the point that PRB coal was compet-

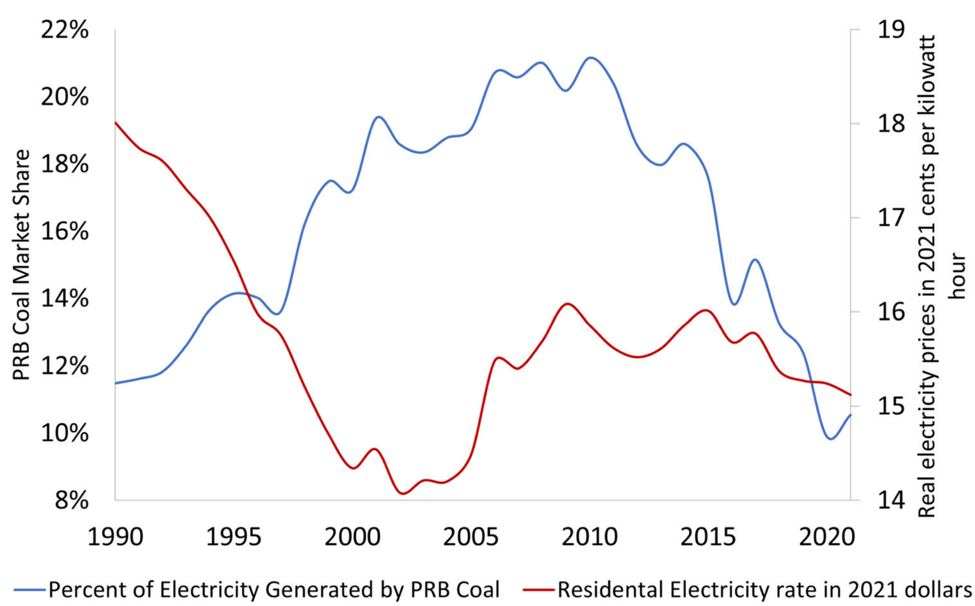


Fig. 5 Comparison of electricity rates between 1990 and 2021 to PRB coal market share [31, 36, 38]. The figure provides the real electricity prices in cents per kilowatt hour in 2021 dollars and compares that to the PRB coal market share of electricity production in the USA

itive with eastern US thermal coals [1]. This, coupled with increasing environmental pressures, facilitated fuel switching from eastern thermal coal to PRB coal. The switch in coal source contributed to decreasing US sulfur dioxide emissions from 13.5 thousand tons in 1997 to 5.4 thousand tons in 2010, representing a 60% decrease [2]. PRB coal has assisted with providing a stable fuel source for power generation while reducing emissions and electric rates [2].

1.3 Challenges Impacting Producers in the Powder River Basin

Producers in the Powder River Basin have experienced a variety of challenges over recent decades. Figure 6 shows historical production from the Powder River Basin beginning in 1983. Coal production increased from approximately 91 million tons in 1983 to a peak production of over 467 million tons. Since the peak in 2010, overall production has been decreasing. It is also noted that during the same time period, production volatility has increased with year-over-year production variances averaging 10% since 2016 with a maximum year-over-year production variances in excess of 20% in 2016 and 2020.

In addition to demand variability, commodity price volatility has become an increasing concern. Coal pricing prior to the COVID-19 pandemic had remained low but stable, with an average change in price of less than 5% year-over-year between 2016 and 2020. Since world economies have begun to emerge from the pandemic, pricing for commodities, in general, has increased, but the Powder River Basin has seen significant volatility in pricing with a 160% increase in 2021 and a 45% decrease between January 1, 2022, and June 10, 2022. Figure 7 shows the volatility seen for the spot price of Powder River Basin coal between 2016 and June 2022.

Historically, utilities set their pricing in long-term contracts which provided both producers and consumers price stability. In recent years, utilities have moved towards spot contracts as power markets and generation strategies have evolved. Electricity producers have begun to reduce the use of long-term contracts which has had a negative impact on mine operations. These long-term contracts allow producers to generate production plans with a greater confidence that the coal volumes scheduled will be the same as the coal volumes sold throughout the planning horizon. Spot market purchases between 2010 and 2021 increased from 7% to 12% of coal receipts [40]. A marked decrease in spot purchases occurred in 2020, as overall deliveries were impacted by lower demand. Spot sales have impacted the industry by increasing demand uncertainty resulting in difficulty planning the operations. While mines attempt to remain flexible, the large-scale nature of the operations makes it difficult to increase or decrease production drastically from month to month. Couple this with rail service variability, commodity price uncertainty, and variable input prices, agile planning processes become even more important. Figure 8 shows the variability in diesel prices which is a significant operational cost for area coal mines. Additional challenges related to the supply chain, rail transportation availability, and the continuing evolution of the power generation sector have made producers focus on becoming more agile in their planning and design practices.

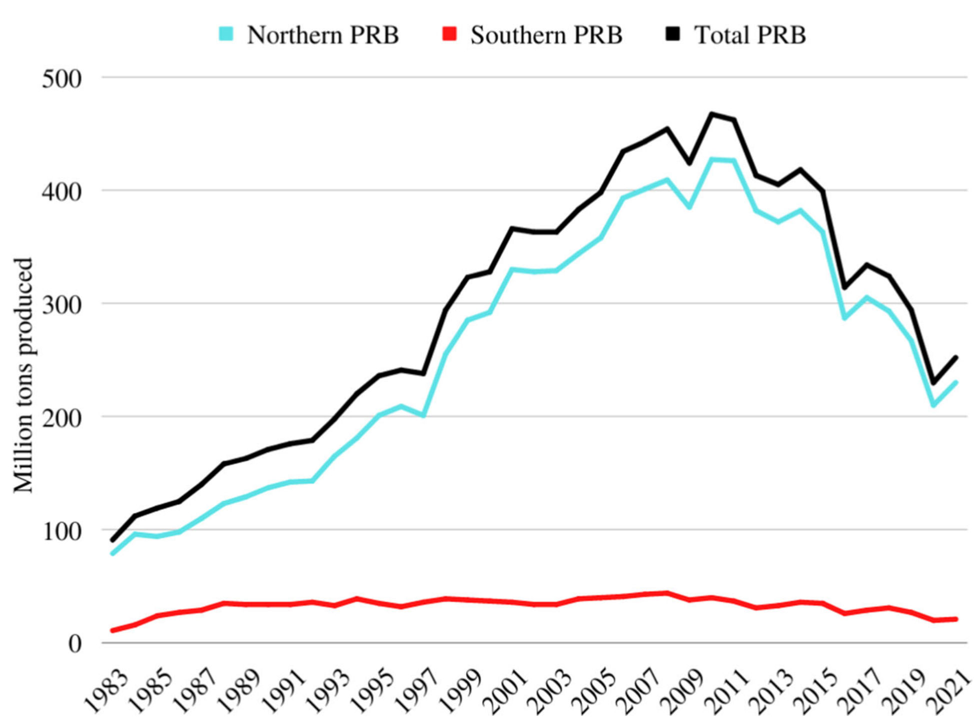
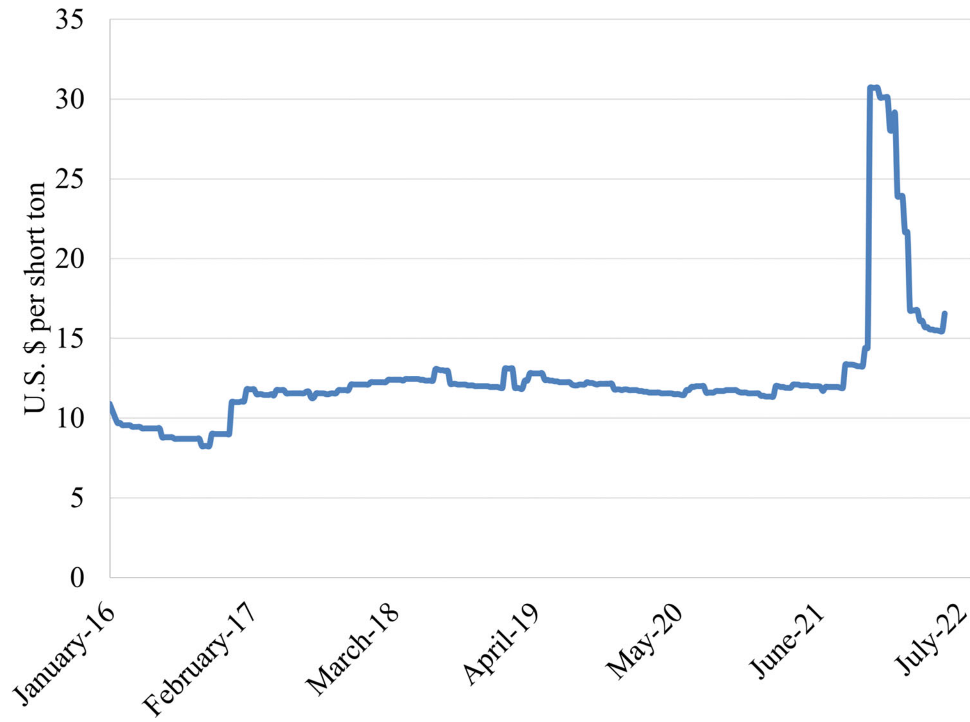


Fig. 6 Powder River Basin coal production between 1983 and 2021 from northern and southern regions with total production [15]

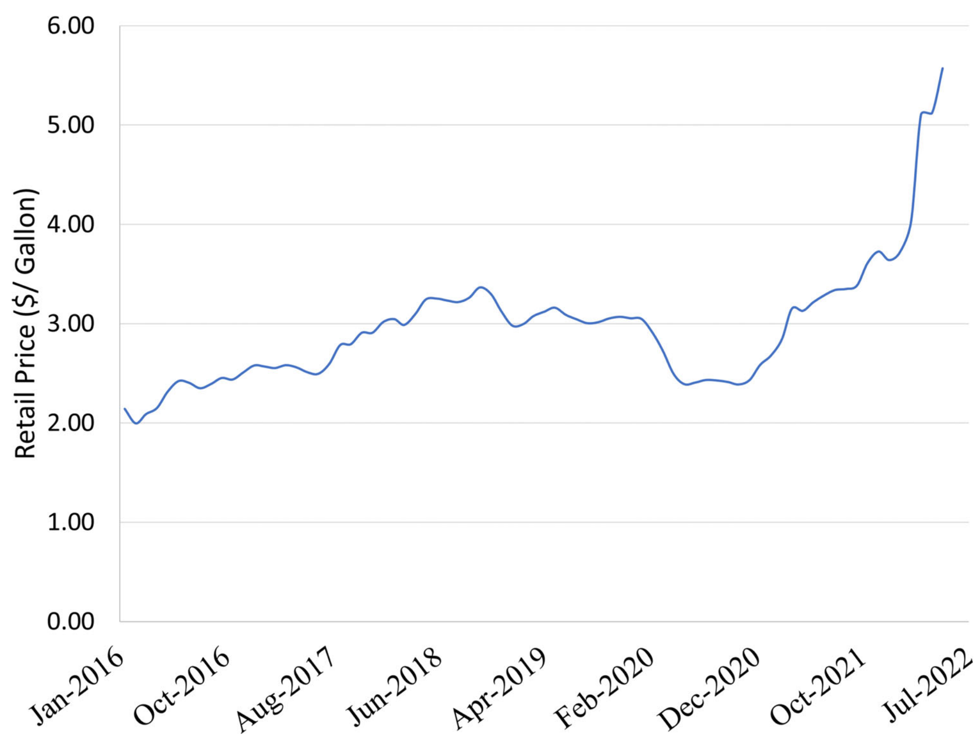
Fig. 7 Weekly 8800 BTU spot price for Powder River Basin coal 2016–mid-2022 [39]



1.4 Powder River Basin Mine Planning Survey

Few details on the current mine planning and production scheduling process exist in the literature for the PRB, with many of the most recent publications available on this topic approaching 25 years old. A series of articles published in 1994 discussed production in the Southern Powder River Basin [26], including an article by Church and Kost [11], that discusses the use of large-scale truck and shovel fleets and an article by Mourich [22] examines the current state of dragline operations. An overview of the coal markets is provided by Vaninetti and Worrall [42] while Willis [43]

Fig. 8 US retail diesel pricing between 2016 and 2022 [41]. The figure shows the variability in US retail price per gallon for diesel fuel between 2016 and 2022



discusses rail service to the PRB. Finally, Glass [44] discusses the geology of the coal fields of the southern Powder River Basin. In 1998, after a technical session at the Society for Mining Metallurgy and Exploration Annual Meeting titled "Continuing change in the Powder River Basin", a series of six articles were published that discussed the current state of operations in the PRB. The articles published by Glass and Lyman [19], Roness, Turpin, and Young [1], Best and Wright [45], Miller and Long [5], Willis and Cunningham [46], and Weakly [28] provide updates to the 1994 articles. Details on challenges, as well as solutions, are described in both sets of articles. Additional discussion on the available literature has been included throughout the paper and specifically in Sections 1.1 and 3.

Yet, PRB companies are still facing challenges that extend further than environmental regulations and pressure to transition from fossil fuels to green energy sources. Volatile commodity prices and consumable costs, e.g., diesel fuel, explosives, along with reduced engineering manpower, have necessitated flexible mine planning and production scheduling methods. The implementation and use of technology are necessary to improve the mine planning process and assist in decision-making. While in the past, mines have remained competitive through infusions of capital and new equipment, constrained cash flows and limited capital preclude the implementation of new equipment to lower unit costs. Concerns also remain as to the longevity of the operations, with many mines focused on surviving the short-term challenges even if there could be a long-term, negative financial impact. Announcements of early power plant retirements, federal coal lease moratoriums, potential increases to the royalty rate assessed on federal coal, and Non-Governmental Organizations (NGOs) protesting the production of coal all represent additional challenges experienced by the industry [47, 48].

In an effort to provide an update as to the state of mine planning practices in the Powder River Basin, a short survey on mine design and production scheduling was shared with mine planning and scheduling departments at active mines. Responses were solicited from mining engineers or those responsible for mine design and planning at both captive and non-captive mining operations in the northern and southern portions of the PRB. A wide cross section of operations, varying from coal production volumes of 63 million tons to less than 2 million tons in 2021, were contacted, with nearly all mines providing detailed responses to the survey. In conjunction with the survey, respondents provided clarity to their responses and additional details via follow-up discussions (virtual meetings) or mine visits. Respondents to this report represent 13 of the 15 mining operations throughout the northern and southern Powder River Basin and six of the eight mining companies operating in the PRB. Data from interviews with mining professionals throughout the Powder River Basin is detailed throughout the remainder of this paper.

The remainder of this paper is laid out as follows. Section 2 describes background information on area mine design and production scheduling, Section 3 provides a review of relevant literature not covered elsewhere, Section 4 discusses the project's methodology while Section 5 discusses survey results, and Section 6 discusses conclusions and potential future research.

2 Background

The area mining method is often used to mine large, flat lying deposits that utilizes sequential cuts, of greater length

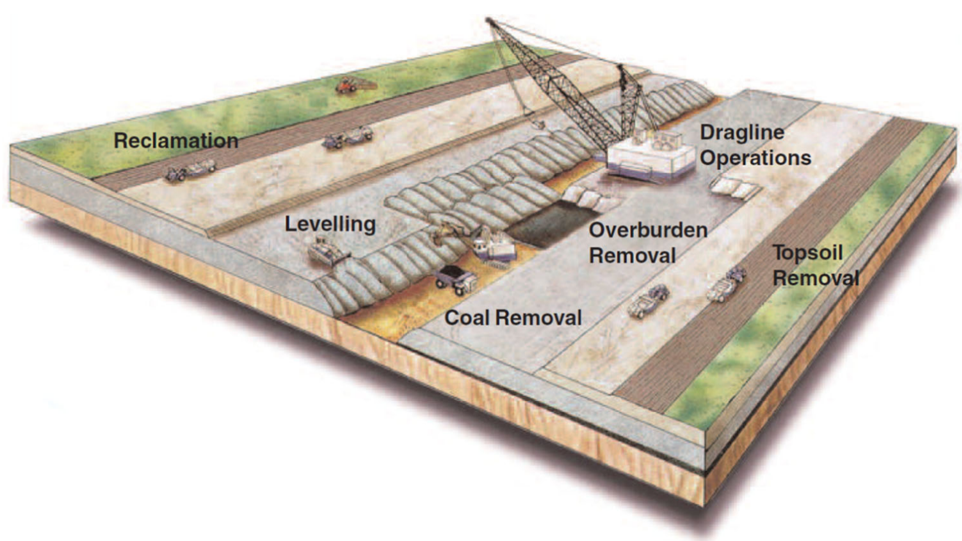


Fig. 9 Depiction of unit operations of an area mine from topsoil removal to final reclamation for an operation using a dragline for overburden removal [7]

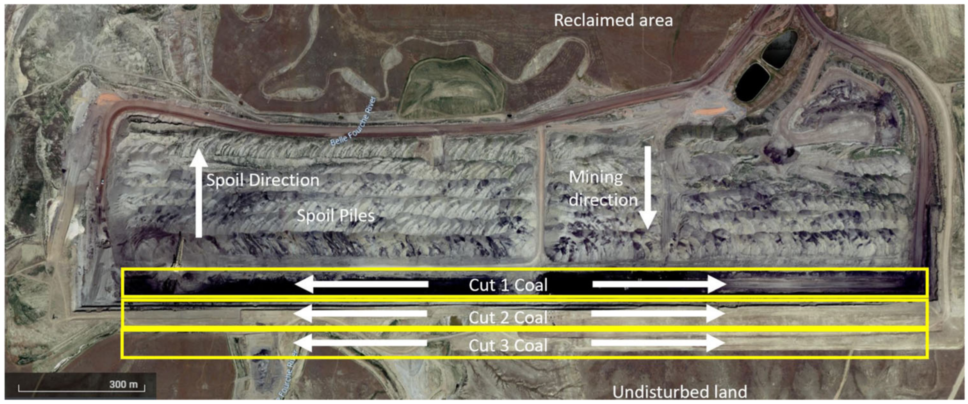


Fig. 10 Example of dragline mine layout from PRB mine showing cuts, contemporaneous reclamation, spoils, and mining direction. Adapted from [49] Photo by: [50]

than width, in a consistent direction [6]. Overburden, i.e., waste material overlying the coal, is placed in previously mined cuts. Excavation of overburden material is typically completed with a combination of equipment types including electric cable shovels, hydraulic excavators, front-end loaders, and draglines. The most common applications in the Powder River Basin are draglines and electric cable shovel fleets. Overburden removed with draglines does not require the use of trucks. Draglines move the overburden to the final destination — a spoil pile in a previously mined cut. Draglines, because of their size, require support equipment such as dozers and excavators to help prepare the working surface and improve dragline efficiency. For mines not utilizing a dragline, electric cable shovels, or other excavators, mine the overburden in successive benches and load the material into trucks until coal is uncovered. Either variation of overburden removal for the *area mining* method will utilize a truck and shovel fleet to mine the coal [8]. Figure 9 shows an overview of an area mine layout for a mine utilizing a dragline as the main source of overburden removal.

Mines using draglines are easily identified by the spoil piles generated by the dragline casting overburden to uncover coal while mines with truck and shovel fleets create benched waste dumps. Figures 10 and 11 depict a typical area mine

Fig. 11 Example of truck and shovel mine layout from a PRB mine showing mining benches, contemporaneous reclamation, waste dumps, and mining direction. Adapted from: [49] Photo by: [51]

progression in plan view showing the pit cuts and spoil or waste dump placement for dragline and truck and shovel fleets, respectively.

The mining of overburden with truck and shovel fleets provides more flexibility in design and sequencing compared to the use of a dragline. When an operation requires greater flexibility for a variety of reasons, e.g., coal blending, truck and shovel fleets are often preferred because of the ability to quickly adjust the design or move equipment to other areas of the mine [6]. A truck and shovel operation can provide a substantially larger coal face which provides easier access to different coal qualities, whereas draglines have a much smaller active mining face. For example, in Fig. 11, there is approximately 900 m (2952 feet) of open coal face available for mining while Fig. 10 shows approximately 80 m (262 feet) of coal face exposed. Both mines have significant in-pit inventory, i.e., coal uncovered not yet mined. To manage blending at a dragline operation, mines may have multiple pits, but that also requires multiple draglines or long travel times when moving from one pit to another, either way, there is a significant cost, i.e., capital cost or lost production, to the operation.

Many mines in the Powder River Basin are focused on meeting contractual obligations with only a small portion of the coal being sold on the spot market [52]. Each coal fired power plant is built to specific coal quality requirements, e.g., BTU or sulfur percent [1]. Therefore, coal and energy producers enter into contracts to ensure that the specific coal qualities and tonnages are mined and delivered to the electric generation facility. These agreements allow the coal mining companies to preemptively design and schedule the mine operations to meet the desired tonnages and qualities.

In addition to contractual obligations, mines in the northern Powder River Basin are limited in the amount of coal that can be stockpiled, i.e., mined but placed in temporary piles outside of the pit. Mines in the southern Powder River Basin are often unable to stockpile coal due to the fugitive emissions control plan requirements regulating open coal stockpiles [53]. While open coal stockpiles are not specifically outlawed, concerns with spontaneous combustion, dust control, and volume monitoring preclude their use. Operations located in Montana have the ability to stockpile coal, but are limited to a permitted volume. To meet these requirements, many operations have constructed silos or barns, i.e., enclosed coal storage, to maintain a desired level of salable inventory. Storage capacity is often limited to less than a week's production and some mines only have storage capacity for less than a day. Capital costs related to adding storage capacity are often prohibitive. This has led to the use of in-pit inventory which ensures that the necessary coal tonnage and coal quality are available to meet contractual demand in the event that the mine experiences a disruption, either planned or unplanned. These types of disruptions may include unscheduled equipment downtime or reduced utilization related to weather or other uncontrollable events. A site's desired inventory level depends on the mining method used, quality requirements, and corporate objectives [54]. While larger inventories provide a higher assurance that shipment requirements are met, they come at a cost of increased waste movement to uncover unsold coal.

2.1 Area Mining Extraction

Three equipment-related mining method distinctions that fall under the umbrella of *area mining* are utilized in the Powder River Basin. These are (i) truck and shovel, (ii) cast-doze, and (iii) dragline [6]. Mine sites may employ a single method or a combination of these methods for overburden removal. Coal removal is then completed by a truck and shovel or truck and loader, e.g., front-end loader, fleet.

For mines using cast-doze, i.e., production dozing, and some dragline operations, the overburden is blasted using a special technique called *cast blasting*. This blasting technique is used to "throw" the overburden material into the previously mined cut. Approximately 20–30% of the material is *cast to final*, i.e., percentage of rock that is not mined by equipment after the blast. This blasting technique reduces the amount of material that must be pushed with the dozers or moved with the dragline [9, 55]. With draglines, a portion of the material not *cast to final* is pushed by dozers to create a working surface for the dragline to mine the remaining material. For cast-doze operations without a dragline, dozers push all of the remaining overburden to the spoil area [6]. The

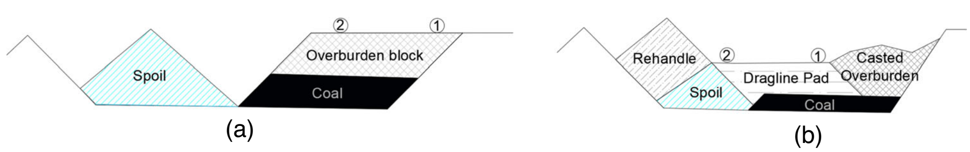


Fig. 12 Main dragline methods used in dragline mines in the Powder River Basin. Numbers indicate dragline placement during respective passes. (a) depicts the side cast method while (b) depicts the multiple pass method Adapted from: [6]

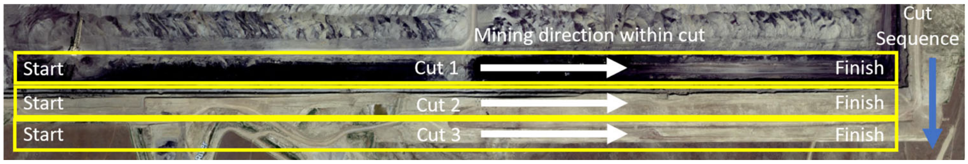


Fig. 13 Deadheading dragline pattern in plan view. White arrows depict the dragline's mining direction within the cut and the blue arrow indicates the extraction sequence of the cuts. The dragline's mining sequence is depicted by the start and finish locations within the cut. Adapted from [56]

cast-doze mining method is utilized for shallow overburden depths, typically less than 30 m (90 feet) [6, 56].

For many deposits, the pit layout or geometry is influenced by the depth of overburden, thickness of coal, geotechnical considerations, and equipment operating parameters. For operations with a low strip ratio, narrower pit geometries, i.e., cut widths, are used to maximize the dragline's reach. This is referred to as the side cast method [5]. Operations with higher strip ratios widen their cut width and incorporate multiple pass mining to reduce the prestrip requirements of the truck and shovel fleets even though rehandle volumes increase. These methods are depicted in Fig. 12 as (a) and (b), respectively.

In addition to the various pit geometries and methods described, a variety of dig sequences may be used in area mines. A deadheading pattern, as depicted in Fig. 13, is a dragline dig pattern in which the dragline walks to the beginning of a cut from the end of a cut after completion. This dig sequence has increased time where the dragline is unable to dig, whereas a layover pattern, Fig. 14, requires the dragline to wait until material is available in the next sequential dragline cut but reduces the walk time significantly [56]. In the layover method, the dragline must wait until all coal is extracted from the cut prior to beginning to uncover the next cut in the sequence. This can be problematic if significant in-pit inventory is required. A third dig pattern depicted in Fig. 15, which is not extensively discussed in the literature, is the *figure-8* dig pattern. This pattern reduces the delay time related to deadheading between cuts, but complicates the mining sequence and operational planning. For the *figure-8* pattern, the dragline begins excavating overburden at the center of the cut, i.e., the crossover point, rather than at one of the ends. The dragline then proceeds to one end of the cut, completing the first pass and mining a portion of the overburden thickness. On the second pass, the dragline digs towards the crossover point to uncover the coal. The dragline then begins the first pass of the second half of the cut. Finally, the dragline uncovers the remaining half of the cut. Once completed with the final pass, the dragline is once again at the crossover point and moves into the next cut sequence.

Several other mining techniques have been attempted in the Powder River Basin but few details exist of their implementation. This lack of information could be attributed to the methods unsuccessfully implemented in the region. In the early 1990s, a surface miner was tested to extract parting, i.e., waste material located between coal seams, at the Rawhide mine, but was relocated to a Russian coal mine despite the test being deemed somewhat successful [26]. In another attempt at employing non-traditional overburden removal methods in the PRB, Caballo mine tested a bucket wheel excavator, but adverse ground conditions led to the discontinuation of its use [26].

2.2 General Area Mine Planning Processes

Mine planning requires the determination of a mining sequence that indicates when, where, and how much to mine to meet the production goals of the operation. The mine planning process includes the interpretation of the geologic model and the development of mine designs, production schedules, and operational economics [10]. Drillhole or other sampling data is compiled into a block or grid model which is utilized in the mine design process. The resulting mine design is then used to determine a production schedule using operational parameters and without violating constraints such as equipment capacities, processing capacities, labor availability, and

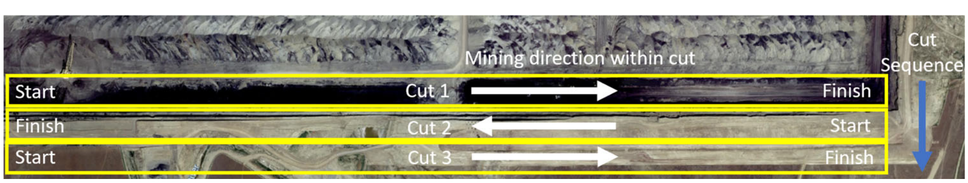


Fig. 14 Layover dragline pattern with dragline sequence for single pass mining. White arrows depict the dragline's mining direction within the cut and the blue arrow indicates the extraction sequence of the cuts. The dragline's mining sequence is depicted by the start and finish locations within each cut. Adapted from Kennedy [56]

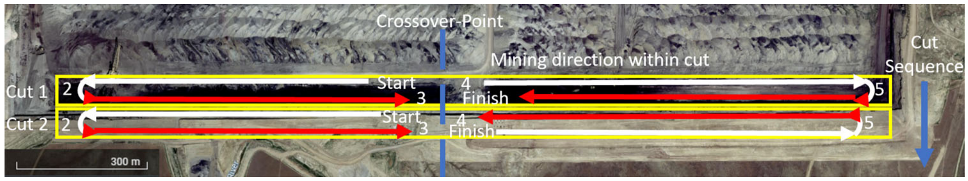


Fig. 15 Figure-8 dragline pattern in plan view with dragline sequence for two pass mining. White arrows depict the dragline's mining direction for the first pass within the cut while red arrows depict the mining direction for the second pass and the blue arrow indicates the cut extraction sequence. The start and finish point for each cut is indicated on the figure, along with numbers representing the dragline sequence. The crossover point is depicted with a dashed line. Adapted from technical report [57]

other operational characteristics. Plans are modified when new exploration data is received or when operational goals or capabilities are modified. The mine planning process is iterative and is conducted frequently during the life of a mining operation. For production schedules, operational details and certainty in coal demand increase as the time horizon shortens.

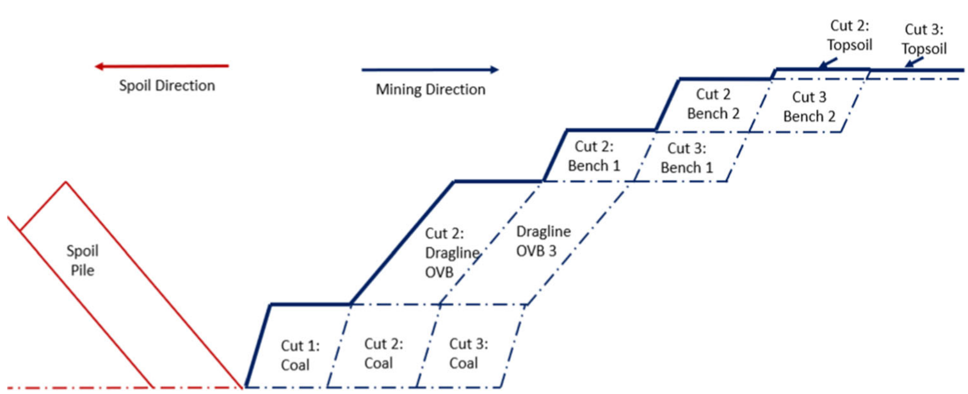
Mine planning for area mines, much like other mining methods, begins with deposit modeling. Unlike metal mines that commonly use block models, area mine deposits are often modeled using grids [58]. Grids are two-dimensional surfaces used to represent topography and geologic characteristics, i.e., top of coal, bottom of coal, or top of parting [59]. Gridded models are used to generate volumes by comparing the depth between two gridded surfaces combined with the pit area. The grids are made up of uniformly sized squares that cover the extent of the known deposit to create what is called a "gridded" surface. These surfaces depict the top and bottom of overburden and coal, among other attributes, to determine associated volumes [57].

Once the deposit has been modeled, pit limits are established based on strip ratio, minimum mining width, highwall slope, and economics [6, 54]. The mine designs are created with industry-specific design software to define the location of the cuts. Once a design has been developed, it can be used to quantify overburden volumes and coal tonnages [60]. Cuts are typically laid out perpendicular to the mining direction which often corresponds to moving from low to high stripping ratio. A typical cross section for a dragline mine is shown in Fig. 16. When the depth of the overburden is more than the available reach of the dragline, prestripping will be used to reduce the depth. Prestripping is typically conducted using truck and loader systems. The number of benches above the dragline mining horizon depends on the overburden thickness, dragline operating height, and geotechnical considerations [56]. While Fig. 16 shows two benches of prestrip, other operations may have no prestripping requirements while others may need more than two benches.

Historically, the development of production schedules for area mines has relied on intuition, experience, and judgement [61]. Area mines can differ from open pit mines with respect to layout, equipment types, mining sequence, and mining direction [54]. Inventory requirements also impact the production schedule. At present, numerous commercially available tools are used to determine production schedules for open pit mines, yet these same tools do not necessarily translate to application at an area mine. Because of the lack of available software tools in the past, many operations developed manual scheduling techniques, some of which are still used today.

Whether using software for generating schedules or manual methods, mines schedule a variety of combinations of equipment and mining direction and then compare the scenarios to determine the best scenario that satisfies the operation's long-term objectives [54]. Manual schedules determine equipment requirements and the mining sequence via user-generated equations and inputs using a common spreadsheet program.

Fig. 16 Typical dragline area mine pit cross section showing cuts for coal, dragline overburden, prestrip benches, and topsoil as well as spoil progression. Adapted from [6, 9, 57]



In comparison, software-generated schedules use a combination of embedded calculations, design software output, and complex user inputs to determine equipment requirements and the mining sequence [62]. Mine schedules generated via software techniques require inputs such as volumetric data, planned operating days, and equipment production parameters. Many of these schedulers utilize heuristics that can provide feasible schedules, but cannot guarantee the optimality of the results [63]. Output from these software packages is often viewed in the form of a Gantt chart, but many have also been integrated with enterprise software [62]. Scheduling software packages may use a completely automated scheduling process or allow users to modify the inputs throughout the scheduling process [64].

Mines often have multiple mine plans that represent various time horizons and levels of detail. For very detailed plans, the time horizon will be short, referred to as a short-term or short-range plan. For longer time horizons, the data fidelity will be reduced. These longer plans are referred to as medium-term or mid-range (less than 5 years) and long-term or long-range (greater than 5 years) mine plans. Some further divide their long-range plan into a long-range plan and life-of-mine plan, with the long-range plan focusing on the first 5 years of the time horizon, as reported in the survey, and a life-of-mine plan covering the time needed to extract the known deposit. The determination of when and where to mine is defined in the production schedule using a given mine design. Both the manual and software-generated scheduling methods can take significant time to complete and do not provide the guarantee of an optimal schedule [63].

Mine planning software packages applicable to bedded deposits include, but are not limited to, Maptek's Vulcan [65], Datamine's MineScape [66], Deswik's Deswik.CAD [64], and Carlson's surface mining module [67]. Mine design software may have schedulers integrated into the software package such as Carlson's Scheduling and Timing Module [67] or Deswik's Deswik.Sched [64]. These integrated design software packages may or may not be utilized depending on corporate or operations philosophies [60]. Mining operations may utilize a scheduling component within the design package or use a standalone software such as RPM's XPAC and XACT [62] depending on whether strategic or tactical mine planning is being completed.

2.3 Technologies Utilized in the Powder River Basin

With the advent of Global Positioning Systems (GPS) in the 1990s, many mines began to employ fleet dispatch systems and grade control applications [5]. Systems, such as Caterpillar's MineStar Terrain [68], Modular Mining's DISPATCH [69], and Hexagon's Jigsaw Operations Suite [70], have evolved to monitor material movement, provide real-time feedback, and reduce the need for a survey crew [5, 28]. Data generated by these systems has also streamlined reporting of key performance indicators and realized production metrics. High speed radio networks, coupled with the ability to easily transfer design files to equipment, have assisted with grade control and reduced rework to ensure that as-built matches design.

Mines in the Powder River Basin have employed cutting edge technologies and new equipment to help ensure that they maintain a competitive edge over other coal basins [5]. Historically, these changes have allowed mines to reduce operating costs, but the restriction of capital, uncertainty of markets, and the future of the industry have limited the implementation of new technologies in more recent years [71]. In addition, capital costs have increased as environment, social, and governance (ESG) demands have reduced the number of lenders willing to provide capital to coal producers [71].

3 Literature Review

Literature on the scheduling and design practices in the Powder River Basin is limited especially with respect to current practices. Few documented details exist on PRB mines other than a few, relatively vague, technical reports by publicly traded companies like [20, 21]. Details from these reports as well as literature from other coal producing basins are provided throughout this review.

A 2022 Weir International NI-43-101 Technical Report on the Black Thunder Mine [21] describes some information related to the mine plan but does not provide detail on the mine planning process or tools implemented, other than the geologic modeling techniques. Similarly, Clayton and Lohkamp [20] describe the mine sequence and production of the North Antelope Rochelle mine in a 2022 NI-43-101 Technical Report, but do not provide details of the mine design and scheduling process.

Miller and Long [5] describe the implementation of design software packages in the late 1990s and the use of computer technology to generate operational plans at mines throughout the PRB. In addition to design software, Miller and Long [5] discuss the use of dispatch systems to assist with updating key performance indicators and monitoring material placement throughout mines in the PRB. Weakly [28] indicates the use of special software programs for mine and reclamation planning and online coal quality analysis, but does not specify the software by name or capabilities. Ronness, Turpin, and Young [1] emphasize the importance of blending for Powder River Basin mines to meet contractual quality requirements while maintaining profitability, but provide few details outside of operational changes to manage the blending requirements. Investment in batch loading facilities, ensuring that coal sampling systems and laboratories provide reliable results, and the addition of train car treatment facilities, e.g., dust suppression, provide mines with additional tools to meet customer demand efficiently. Weakly [28] further discusses the use of batch loading facilities and the highly skilled workforce that is present in the PRB. Wilkenson [72] documents a 60% decrease in time to produce long-range mine plans by integrating geologic modeling, mine design, and production scheduling into a single, integrated mine plan using Mincom MineScape software to replace an existing mine design software package. These improvements were seen at a truck and shovel mine in the western United States with an annual production rate of approximately 25 million tons. Wilkenson [72] does not mention the name or location of the case study mine, but all surface coal mines producing over 15 million tons around the time of publication were located in the PRB [15].

Mourich [22] describes the initial implementation of draglines in the Powder River Basin and the rapid adaptation of the mines. Miller and Scott [73] provide engineering and operational details of the relocation of a dragline from the Coal Creek Mine to the Black Thunder mine in 1991. Martin, Stump, and Pearson [74] detail the design and implementation of cast blasting, a key scientific breakthrough surrounding the transition from small truck and shovel fleets to large-scale dragline operations, at the Black Thunder mine. In addition to design and operational practices, the authors describe experiments to determine if there exists seismic differences between nuclear explosions and large surface chemical blasts [74]. The authors evaluate seismic waves for the different explosions and determine unique signatures to identify the type of detonation to prevent public concern or international conflicts. King and Hejny [75] give details surrounding the blasting techniques of the early 1990s while Brandt [76] describes the mining process at Rawhide mine in the early 1980s, including the design parameters used for coal and overburden blast designs. While the literature provides clarity on the design parameters used in the 1980s and 1990s, no discussion exists regarding the tools and technologies of the production scheduling process other than a discussion on the use of GPS for surveying.

Other coal basins have implemented a variety of mine scheduling and design practices. Deist and Roberts [77] provide clarity on the use of simulation for South African coal mines using a file maintenance system and a production simulator to generate production plans. The simulation calculates the operational and financial metrics of alternative mine plans. In Australia, Just and Aspinall [78] discuss the use of SURPAC, XPAC, and TALPAC in conjunction for mine design, scheduling, and truck and loader simulation, respectively. Whitchurch, Cramm, Ozawa, and Koizump [52] describe the complexity of scheduling coal mines and the importance of evaluating multiple options. Furthermore, the authors recommend the use of artificial intelligence (AI) methods to reduce the time required for comparison of multiple mine production schedules. Describing the use of simulation for dragline operations in Australia, Baafi and Mirabediny [59] outline a program, called DSLX, designed to simulate draglines for both short and long-range planning purposes. Simulations are compared on a cost analysis basis to determine the preferred dragline pattern. Harvey and Holmes [54] describe the mine design and production scheduling process for a coal mine in New Zealand and the use of computer-aided design to meet the highly variable quality demands of customer contracts. The use of Maptek's Vulcan assists with generating schedules, but the authors describe an iterative and laborious process to determine the mine production schedule.

A variety of operations research techniques have been suggested for bedded deposits but none using case study mines within the PRB. Gershon [79] details theoretical applications of mathematical programming to area mines. These applications include linear programming for scheduling optimization, blending, and transportation. In another theoretical attempt, Halatchev and Kozan [80] schedule a hypothetical coal mine using linear optimization and "block-by-block" scheduling similar to that used for open pit mines. Results from their attempt provide a mathematically feasible schedule that falls short operationally, with significant variations in waste volumes year-to-year, as admitted by the authors. In an attempt to determine the production strategy for a system of Brazilian coal mines, de Carvalho Junior, Koppe, and Costa [81] use stochastic linear programming to quantify the uncertainty of production to determine the mine output that maximizes the operational contribution of the mining complex while meeting processing capacity and demand for multiple coal products. Jerez [82] describes a single period linear model used to determine output for a mountaintop removal operation in Kentucky. Jerez and Tivy [83] describe the use of linear models to determine production output and quality for an underground coal mine in Pennsylvania, a system of surface coal operations in Colorado, and a surface coal operation in West Virginia. In an attempt to integrate waste placement for a surface coal operation, Das, Topal, and Mardenah [84] provide a schedule for a theoretical mine consisting of 18 blocks using a formulation described by Fu, Asad, and Topal [85] for an open pit operation. Improving upon solutions by Das, Topal, and Mardenah [84], Das, Topal, and Mardeneh [86] describe the scheduling of a coal deposit using a lag constraint to limit waste placement for a mine design generated from a sample data set in a design software package. Neither publication from Das, Topal, and Mardenah [84, 86] cite any coal literature in their works and do not include blending constraints in their models. Meaning that if coal is below the contract specifications it is treated as waste rather than blended with higher quality coal to meet specifications as required of mines in the PRB. Blocks depicted by both publications [84, 86] combine coal and waste material while modeling techniques used in the PRB generate volumes for coal and waste separately.

4 Methodology

Mine design and production scheduling have evolved through the nearly half century of large-scale mining in the Powder River Basin. Changes to the mining environment and the future outlook for the coal industry indicate that current tools may need to evolve to accurately reflect the new business conditions. These evolving needs may require changes to existing processes or the development of new processes to meet the challenges associated with uncertain demand, commodity price volatility, supply chain disruptions, and professional and skilled labor shortages. In order to evaluate the future production scheduling needs of operations in the PRB, it is important to understand the current practices. The authors developed a survey and received responses that document the mine design and scheduling practices in the Powder River Basin.

A total of 9 survey responses were received from professionals responsible for mine planning at 13 mines in the northern and southern Powder River Basin. In addition to completing the survey, 7 interviews were conducted with the same mining professionals between the dates of June 9, 2022, and August 26, 2022. Henceforth, data from these surveys and interviews is categorized by the interview session and the session attendees are referred to as a single “respondent”. Information collected during the interviews included details on their mine planning processes and challenges encountered at the specific operations. Each respondent provided answers to a standardized survey, included in the Appendix. The survey requested information on the mine planning process, software programs, typical duration for each level of planning, i.e., short-range, mid-range, and long-range, strengths and weaknesses of their current planning process, future planning needs, planning goals, and potential for research collaboration. The interviewees provided a discussion on their planning and design processes, and clarify differences in terminology between companies. At the request of the majority of the companies interviewed, the information collected has been aggregated or presented in a way that precludes identifying information of a specific company or operation.

The respondents’ contributing data for this survey represent operations contributing 97% of 2021 PRB production. Mining practices at the surveyed sites range from purely truck and shovel operations to operations employing a mixture of truck and shovel, production dozing, and dragline methods. Both captive and non-captive operations are represented as well as mines with a wide range of production volumes seen across the PRB. While not all operations provided survey responses, those that did respond represent a large cross section of the Powder River Basin operations.

5 Results

Evaluating the responses shows a variety of mine design and production scheduling methods employed across the Powder River Basin. Mines utilize a variety of mine design software packages and a mix of software and manual methods for scheduling. While all respondents indicate completion of short-range, mid-range, and long-range plans, significant variation in the schedule length and fidelity exists across the PRB. A variety of challenges are expressed by respondents with suggestions for updates to the mine planning process specific to PRB operations.

5.1 Software Commonly Used in PRB for Mine Design and Production Scheduling

While a variety of design and production scheduling software programs are applicable to area mines, the Powder River Basin operations employ a small number of related software packages. Of the mines surveyed, 61.5% indicate the use of multiple design packages in order to meet their needs rather than a single solution. Only three respondents indicate the use of a single software solution. 40% of respondents indicate the use of multiple methods of production scheduling, depending, on the scheduling time horizon. Truck and shovel operations are more likely to use a single design software package than mines employing draglines for overburden removal in conjunction with a truck and shovel fleet completing prestripping. 75% of respondents from dragline operations are using one software package for detailed design work, i.e., ramps, roads, environmental design, and short-range plans, and a second design package for generating volumes and tonnages for mid-range and long-range scheduling purposes.

The most common design software in the Powder River Basin is Carlson (Surface and Civil Modules) [67]. 70% of respondents indicate the use of Carlson’s modules for mapping and reporting for regulators. Of the companies employing Carlson’s modules, all but one use it in conjunction with another mine design software. Other design software packages currently employed across the PRB include Maptek’s Vulcan [65] and Datamine’s MineScape [66].

Production scheduling methods vary across the mine operators and individual mines as well. 100% of respondents indicate that their mines are utilizing Microsoft® Excel® [87] spreadsheets at some level of their mine planning process with 85% of respondents using spreadsheets that have been generated by their engineering staff for short-range

Table 1 Mine planning and production scheduling programs in the Powder River Basin

Program Type Design (D) Scheduling (S)	Program Name	URL Location
D	Carlson Civil Module	https://www.carlsonsw.com/product/civil-suite/
D	Maptek Vulcan	https://www.maptek.com/products/vulcan/open_pit.html
D,S	Maptek 3D Dig	https://www.maptek.com/partners/3d-dig/
D,S	Carlson Surface Mining	https://www.carlsonsw.com/product/surface-mining
D,S	MineScape	https://www.dataminesoftware.com/solutions/ minescape-geological-modelling-mine-planning/
S	Micromine Spry	https://www.precisionmining.com/
S	XPAC	https://rpmglobal.com/product/xpac/
S	XPAC Solutions	https://rpmglobal.com/product/xpac-solutions/
S	XACT	https://rpmglobal.com/product/xact/
S	Microsoft® Excel®	https://www.microsoft.com/en-us/microsoft-365/excel

scheduling. 40% of respondents are utilizing spreadsheet methods for either mid-range or long-range planning, but others are using a mix of scheduling packages. In addition to RPM Global products mentioned previously, one respondent indicated that their planning engineers have begun testing a new software, Micromine's Spry [88].

Additional information related to the design and production scheduling programs in use in the PRB can be found at their respective websites included in Table 1. It should be noted that this is not an exhaustive list of mine design and production scheduling programs available, but does report on all software from the survey responses. 80% of producers using production scheduling software indicate the use of separate design and production scheduling programs even when the design program includes a scheduling module.

5.2 Variations in Planning Process and Systems Across the Powder River Basin

A variety of planning practices and systems are in place across the PRB. All respondents indicate the completion of schedules for short-range, mid-range, and long-range planning, but the schedule length and fidelity vary for short-range and mid-range planning depending on the mine and/or corporate structure. 60% of respondents providing details for multiple mines operating under the same corporation indicate differing processes between their mines with little to no corporate-wide guidelines or other documentation outlining the process for mine design and production scheduling. Table 2 shows the planning frequency for each respondent in the survey for short and mid-range planning functions while Table 3 shows long-range planning and life-of-mine planning frequency. It should be noted that one respondent may provide details for multiple mining operations under a single corporation.

The survey responses report a significant variation in the duration of plans for short-range planning. 71% of mines complete a short-range plan for the current week with an accompanying monthly plan. Other sites complete a short-range plan length of up to 90 days. Mid-range plans vary in length from 3 months to nearly 2 years. Mines with shorter mid-range plan time horizons develop plans with greater frequency than those with longer time horizons. Departing from the literature, mines in the PRB subdivide their mine plans with a time horizon of 5 years or greater into long-range and life-of-mine plans rather than simply long-range plans.

Table 2 Mine planning frequency in the Powder River Basin for short and mid-range planning

Respondent Number	Short-Range Duration	Short-Range Frequency	Mid-Range Duration	Mid-Range Frequency
1	6 weeks	Weekly	3 months	Monthly
2	7 days	Weekly	2 years	Quarterly
3	7 days and month	Constantly	3 months	Monthly
4	90 days	Constantly	1 year	Quarterly
5	7 days	1–2 times per week	90 days	Quarterly
6	30 days	Weekly updates with monthly full revision	2 years	Quarterly
7	30–60 days	Bi-weekly updates	3–6months	Quarterly

Table 3 Mine planning frequency in the Powder River Basin for long-range and life-of-mine planning

Respondent Number	Long-Range Planning Duration	Long-Range Frequency	Life-of-Mine Frequency
1*	5 years	Annual	Biannually
2*	5 years	Annual	Annual
3*	5 years	Annual	Annual
4	5 years	Annual	Biannually
5	5 years	Biannual	Biannually
6	5 years	Annual	Biannually
7	5 years	Annual	Annual

An (*) indicates respondents that provided the desired planning frequency that is not currently being met

Long-range plans are, in general, completed annually as part of the budget process while life-of-mine plans are completed less frequently for 57% of respondents. Long-range plans provide greater detail than life-of-mine plans. All mines indicated that long-range plans typically covered a 5-year time horizon, but one respondent indicated that they may only complete a 12-month plan if a 5-year plan is unnecessary.

For life-of-mine plans, 42% of respondents mention that they have not updated their plans for several years due to a shortage of engineering manpower. These respondents are noted with an asterisk in Table 3. These respondents indicate their desire to increase the frequency of updating life-of-mine plans, but note that the time required to complete these plans coupled with less available manpower as the reason for their inability to complete at the desired frequency. Larger operations revise their life-of-mine plans more frequently than operations with lower production rates. 28% of mines indicate that the life-of-mine plans take engineers nearly 6 months to complete using current processes. Most long-range and life-of-mine planning in the Powder River Basin takes a minimum of a month per mine operation to complete with potential to extend completion time several months depending on the size and complexity of the mine site.

The majority (67%) of responses from companies with both large and small operations indicate that smaller operations, i.e., those producing less than the PRB mine average, use a different planning process than larger operations within the same corporation. Table 4 provides the planning method for each planning level and the average coal tonnage (millions of tons) produced per engineer, i.e., planning efficiency, at the different operations. Heuristic planning methods refer to those methods using mining-specific software solutions for scheduling while manual methods refer to those methods using spreadsheets for scheduling. Yet, if a respondent represents multiple sites, the planning efficiency represents a weighted average by coal production between all sites using 2021 production volumes and the engineering manpower available. Higher planning efficiency is seen at mines using heuristic methods over those using manual methods. Mines with lower production levels have lower reported planning efficiencies which corresponds with respondents' comments that a site needs a minimum number of planning engineers no matter the production volume. Sites using a combination of dragline and truck and shovel equipment for overburden excavation, on average, produce 1.5 million more tons per planning engineer than those using truck and shovel fleets solely. This difference equates to a nearly 27% higher productivity for dragline operations in relation to their engineering staff. It should be noted that this calculation only includes produced coal tons and ignores any impact from overburden production. Other factors impacting planning efficiency not captured in this statistic may include the complex blending structure, challenging technical conditions, and complex mining sequences. Mines may be more efficient in terms of total material moved than coal produced, but total material volumes are not readily available.

5.3 Challenges with Current Planning Process

Survey respondents note a variety of challenges with the current mine design and production scheduling processes

Table 4 Mine scheduling methods and manpower requirements in the Powder River Basin by respondent

Respondent Number	Short-Range Plan	Mid-Range Plan	Long-Range Plan	Life-of-Mine Plan	Million coal tons produced per engineer
1*	Manual	Manual	Manual	Manual	4.5
2*	Heuristic	Heuristic	Heuristic	Heuristic	4.5
3*	Manual	Heuristic	Heuristic	Heuristic	1.2
4*	Manual	Manual	Manual	Manual	5.1
5	Heuristic	Heuristic	Heuristic and Manual	Manual	9
6*	Manual	Manual	Manual	Manual	8.3
7	Manual	Manual	Heuristic	Manual	2

An asterisk (*) indicates respondent represents multiple mines across the Powder River Basin. The most common challenge for production scheduling is the consumption of manpower resources and the length of time required to generate a feasible schedule for a given mining scenario. 86% of respondents describe manpower shortages at their respective operations, in addition to a lack of experience within their workforce, with the exception of one mine. Similarly, 86% of operations rely on engineers that are nearing retirement to complete planning tasks and are also struggling with recruiting new talent. This, coupled with the time demands of the methods currently available, severely limits the ability of operations to react quickly to commodity price fluctuations, supply chain shortages, and operational cost variations. In addition, all respondents note a variety of attributes, such as haulage modeling, manpower requirements, and tracking coal inventories in greater detail, that are not evaluated within their current processes. The inclusion of these attributes, or others, would provide clarity on their impacts as well as provide a schedule more reflective of their operations.

There is a desire to incorporate a variety of new attributes into mine planning in the Powder River Basin. Nearly 43% of respondents indicate the necessity of generating reclamation and production schedules in an integrated process rather than producing a production schedule and then producing a reclamation schedule that meets the production schedule. Other attributes include modeling impacts of variable production, modeling haulage, automating the scheduling process for mines using manual methods, determining the economics of more selective mining practices in challenging quality environments, and incorporating the premium-penalty structure of the coal contracts rather than a static coal revenue factor. Integrating financial parameters during the design and scheduling phases, rather than determining the financial value of a plan after it is complete, is also a desire of industry respondents.

Plans that are produced using current processes focus on one or two outcomes, e.g., minimizing haul distance, minimizing strip ratio, maximizing cashflow, or a combination of one or two parameters, rather than a holistic planning approach, e.g., integrating haul distance, quality, reclamation, and production scheduling into a single planning process. 71% of respondents describe the need to model and schedule coal blending to meet customer contracts, but indicate the labor and time requirements as limiting factors. More holistic scheduling methods are difficult due to the sheer size and complexity of the production schedules, and when mines use inexperienced mine planners, the time to complete a production schedule increases dramatically. The common practice for mine planning engineers is to generate several different schedules with variable parameters, such as production rates, and select the schedule that best meets the corporate objective. Those using manual scheduling methods are limited by the ability of the engineer producing the schedule while production scheduling software packages using heuristic methods generate an operationally feasible schedule, but not necessarily, or likely, to be the optimal schedule [63].

Mines are increasingly seeing difficulty in projecting rail service as well as parts and supply availability, i.e., equipment repair parts, filters, and fluids, and at times, manpower. Nearly 57% of producers note an increase in the warehouse stock they maintain and express concerns with maintaining their equipment fleet even with increased warehouse inventories. This leads to difficulty in predicting equipment availability which in turn impacts the overburden and coal production at a mine. To adequately understand the impacts of these changes, engineers need to run additional scenarios which further stretches the manpower needs and in many cases leads to short-range planning taking precedence over long-range planning to meet the day-to-day needs of the mine. One respondent indicates, "You can quickly run through a schedule when the sequence remains the same, but when you have to go back to the drawing board to make a sequence work due to no increase in labor, then this creates a challenge". As noted previously, this rapidly changing environment, combined with a labor shortage, has led to a decrease in the completion of life-of-mine plans simply because there is no manpower available to complete them. The loss of this level of planning forces mine planners to rely on historic life-of-mine plans that do not reflect current conditions which may lead to decisions that are misaligned with the state of business in the PRB. 71% of respondents note significant rework in their scheduling process due to equipment availability issues that they had not experienced historically.

Two respondents note the monumental task of transitioning to another scheduling method or program as reasoning for maintaining the status quo. Concerns with implementation delays, difficulty understanding the process used to generate solutions, and difficulties experienced using current technologies are often voiced by engineers. One respondent notes difficulty in achieving a feasible schedule using commercial scheduling software for their operations. 57% of respondents note the setup time for commercial scheduling software as a hindrance for its implementation in short-range planning. The ability for multiple engineers to collaborate in generating a production schedule for an operation is important to many of the industry professionals and is a benefit some respondents see in collaborative commercial production scheduling software packages such as RPM Global's XACT.

5.4 Potential Updates to Planning Process

Interest exists in updating the mine design and production scheduling processes in the Powder River Basin. While there are some available tools, there is interest among operators to encourage research activities that seek to evaluate modifications to existing tools or development of new tools. While open pit and underground metal mines have used optimization methods for decades, area mines have yet to see significant benefit in employing these operations research methods. The operations research methods used by open pit and underground operations are described in depth in reviews by Newman et al. and Chowdu et al. [89, 90]. Operations research methods, described by Das, Topal, and Mardenah for coal operations in Australia [84, 86], could potentially be applied to area mines like those in the Powder River Basin with modifications. While area mines cannot be modeled in the same manner as open pit or underground mines, there are many similarities between the mining methods that could be applicable to the challenges identified in the survey. This presents an opportunity to software companies and researchers to explore new tools for the coal industry. Of the survey respondents, 43% mentioned an interest in future research related to scheduling and design as well as willingness to provide data sets for case studies.

Survey responses indicate the importance of reclamation scheduling in collaboration with production scheduling. As mines age and near closure, theres an increasing focus on reclamation and meeting the reclamation schedule. One survey response indicates maintaining the reclamation schedule as a key driver in their production scheduling process. Reducing the cost of reclamation as margins have thinned has also become important. For many PRB operations, decreased coal demand is generating excess production capacity in current equipment fleets. This is creating the opportunity for mines to limit their output during periods when production costs are high and increase output or maintain when production costs are low. Schedules that are developed with the goal of determining when and how often to operate equipment could greatly reduce costs.

6 Conclusions

A review of the current processes with industry respondents reveals potential for improvement and the desire for tools that provide fast, efficient, and feasible planning solutions. All respondents indicate that there is a need to expand the current mine planning process to consider the new challenges impacting mine designs and production schedules. These parameters include incorporating more complex blending requirements, integrating reclamation planning, and managing energy consumption.

Significant concern arises from the number of respondents indicating the inability to complete life-of-mine plans on a consistent basis due to limited engineering manpower along with the significant time required to complete these plans. Additionally, the uncertain business environment has created a "survival" mentality at many mining operations. While the authors understand the importance of remaining profitable in the short-term to exist in the long-term, the capability to produce long-range mine plans with greater ease would allow operations to evaluate the impacts of short-term decisions and to quickly understand the impacts of the changing parameters as they arise.

Mines using software-based solution methods require fewer engineers per million tons of coal produced than those using manual spreadsheet-based methods. The survey highlights an opportunity for software companies and researchers to develop tools that more accurately model the existing operational challenges and reduce the time and labor requirements to generate production schedules.

Of the respondents, 43% indicate interest in providing data for future research in mine design and production scheduling. Incorporating reclamation and haulage modeling into the production scheduling process was mentioned as a desired focus area by nearly all of the respondents. Respondents agreed that incorporating this key aspect into their scheduling process would provide a more holistic schedule than current methods. Other future research could include determining waste placement that minimizes fuel usage while maintaining a desired extraction and reclamation schedule as well as managing other variable costs, e.g., fuel, energy, labor.

While many question the future of the coal industry, there remains a need for reliable energy and the Powder River Basin has the ability and resources to continue to provide energy for decades to come. In addition, the authors encourage researchers and software developers to not ignore the industry and work to develop tools and methodologies to help this important industry. At the same time, the coal industry must continue to express the need for new tools and the willingness to participate in their development.

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Declarations

Conflict of Interest The authors declare no competing interests.

Appendix: PRB Mine Planning Survey

1. What mine design software are you using at your sites? (i.e., Carlson, MineScape, Vulcan)
2. What activities do you use design software for, design, geologic modeling, surveying, volume calculations, reconciliation, reclamation….etc.?

3. What programs are you using for production scheduling? (i.e., XPAC, Excel)
4. On average, how much time does your planning group dedicate to short-range, mid-range, and long-range planning? At what frequency do you complete these tasks?
5. What strengths do you see in your current mine planning and production scheduling process?
6. What challenges/concerns do you experience with your current mine planning and production scheduling process?
7. What items that you do not currently include in your mine planning process would benefit your operations? (i.e., variable production costs, haulage modeling, other items)
8. What are you making your decisions based on? Cash-flow, NPV, bond, other?
9. What research in mine production scheduling or mine optimization might be of benefit to your operations?
10. Do you have any references or company manuals that you use when determining your planning process?
11. Would you like your company name and identifying information redacted or obscured in the publication of this research?
12. Would you be interested in providing a data set for potential research? Data sets typically need to include volumes related to specific coal tonnages as well as coal qualities. Non-disclosure agreements can be put into place if desired. For companies already providing data, this question can be omitted.

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