
3 FIELD AND LABORATORY INVESTIGATIONS

3.1 Introduction

A systematic set of field work and experiments were performed to achieve the desired objectives. The experiments are planned to generate necessary data for building suitable relationships. Experiments involved both field and laboratory for determining coal, machine and operational parameters along with the key productivity indicators of SM in opencast coal mines. In this study, eight opencast coal mines spreading across India are selected based on deployment of SM for coal production. The coal mining sites are Samaleswari, Lakhanpur, and Bhubaneswari opencast mines of Mahanadi Coalfields Limited (MCL), located in Odisha; Gevra opencast mine of South Eastern Coalfields Limited (SECL) and Parsa East and Kente Basan opencast mine of Hasdeo-Arand Coalfield, situated in Chhattisgarh; Nigahi and Jayant opencast mines of Northern Coalfields Limited (NCL), Madhya Pradesh; and Rajmahal opencast mine of Central Coalfields Limited (CCL), Jharkhand, as described in Figure 3.1. The details of experiments and the adopted procedures are also presented in this chapter.

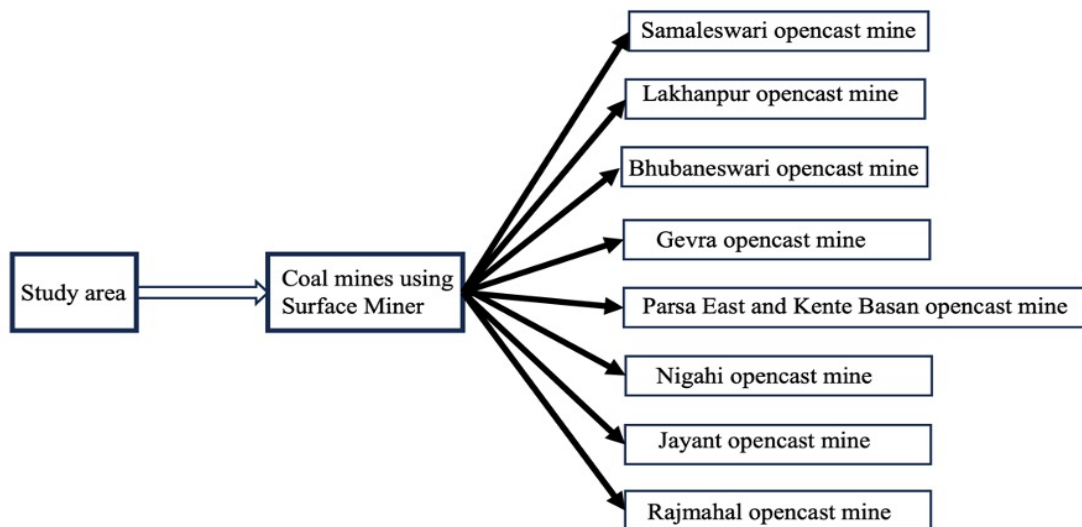


Figure 3.1: Opencast coal mines selected for the study

3.2 Field study

Field investigations offer the invaluable opportunity to gain firsthand experience by exploring, observing, and studying real-world phenomena that cannot be replicated in a laboratory setting. Table 3.1 details five different models of SM, which were deployed to cut low rank, non-coking, power-grade coal seams along with shaly coal and carbonaceous shale bands in Indian opencast coal mines are observed during field study. Mine's location, geology and mining systems are also observed to investigate geo-mining conditions in Indian opencast coal mines, as outlined in Figure 3.2.

Table 3.1: SM models in Indian opencast coal mines considered for study

S.N.	Opencast coal mine	SM model	Brand	SM Count
1	Nigahi opencast coal mine, Singrauli coalfield, Madhya Pradesh.	KSM403	L&T	2
2	Jayant opencast coal mine, Singrauli coalfield, Madhya Pradesh.	KSM403	L&T	2
3	Bhubaneswari opencast coal mine, Talcher coalfield, Odisha.	2200 SM 3.8	Wirtgen	6
4	Rajmahal opencast coal mine, Rajmahal coalfield, Jharkhand.	2200 SM 3.8	Wirtgen	2
5	Parsa East & Kanta Basan opencast coal mine, Hasdeo-Arand coalfield, Chhattisgarh.	2200 SM 3.8	Wirtgen	5
6	Samaleswari opencast coal mine, IB Valley coalfield, Odisha.	KSM 303	L&T	2
7	Lakhanpur opencast coal mine, IB Valley coalfield, Odisha.	KSM 303	L&T	3
8	Gevra opencast coal mine, Korba coalfield, Chhattisgarh.	2200 SM	Wirtgen	4
		2200 SM 3.8	Wirtgen	2
		KSM 304	L&T	2

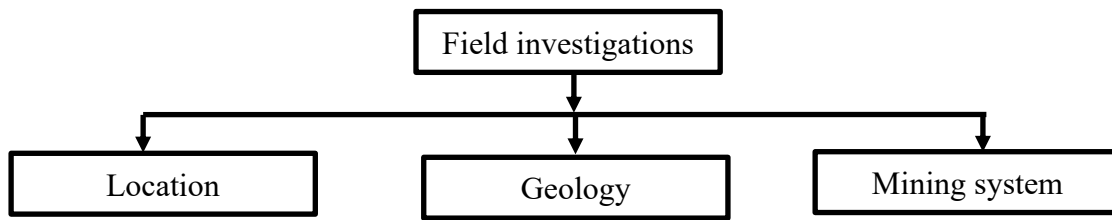


Figure 3.2: Field investigations conducted in opencast coal mines

3.2.1 Nigahi opencast coal mine

a) Location

Nigahi opencast coal mine (NOCM) is located between latitudes 24°06'3.29" and 24°11'16.37" N and longitudes 82°35'28.23" and 82°39'50.12" E in south-central part of Moher sub-basin (area of 312 km²), Singrauli coalfields, Singrauli district, Madhya Pradesh. This mine shares the boundary with Jayant and Amlohri projects on the east and west, respectively.

b) Geology

The entire block area, associated with NOCM, is covered by the sediments of the Barakar Formation. The geological properties of the Barakar Formation for NOCM are detailed in Table 3.2. The stratigraphic sequence of rocks within Barakars is given in table 3.3. The coal horizon comprises coal, shaly coal and carbonaceous. The Barakar sequence mainly consists of fine to coarse-grained, light grey, felspathic sandstone, clay, shale, carbonaceous shale and coal seams. The shale bands generally occur as inter banded with coal and constitutes most of the seam's dirt bands. The general dip of the area is 2° to 3°, without any faults. Figure 3.3 shows the cross-sectional view of NOCM.

Table 3.2: Geological properties of Barakar Formation at NOCM

Age	Formation	Major rock type	Appearance	Particular
Lower Permian	Barakar	Sedimentary rock (Sandstone, clay, shale and coal)	Structure – layers or seams Grain size – Fine	Thickness – 325 to 600 m Texture – non-clastic Colour – dark brown to black, and dull

Table 3.3: Stratigraphic sequence of rocks within Barakar formation for Nigahi block

S N	Lithology	Thickness (m)		Geological reserve (Mt)	Dirt bands (%)
		Min.	Max.		
1	Sand and sub soil	Nil	9		
2	Sandstone with 2 to 3 clay bands and 1 to 2 thin impersistent carbonaceous bands	30.50	167.40		
3	Coal seam: Purewa Merged	18.9	25.7	38.85	23-28.5
4	Coal seam: Purewa Top	4.20	10.94	17.60	4-48.7
5	Sandstone with thin shale bands	1.00	29.35		
6	Coal seam: Purewa Bottom	8.8	14.7	24.1	5.3-43.4
7	Sandstone with thin carbonaceous shale	52.1	69.6		
8	Coal seam: Turra	11.08	19.20	221.56	0-21.6



Figure 3.3: Cross-sectional view of Nigahi opencast coal mine

c) Mining system

The NOCM has a total strike length of 3.5 km, and the working width is 3.4 km. It has been divided into two parts, *i.e.*, east and west sections, separated by a central haul road. Purewa Top and Purewa Bottom merge to form a 17.57 m – 27.5 m thick composite seam in the western part. All three coal seams, namely, Purewa Top, Purewa Bottom and Turra are under extensive exploitation in the block. The OB removal and coal extraction are being carried out using a strip-wise advancing method toward the north of NOCM. OB removal is being carried out using draglines with a combination of shovel and dumper, whereas Coal extraction is being carried out by SM and shovel-dumper combination. Table 3.4 depicts mining system parameters related to NOCM.

Table 3.4: Mining system parameters for Nigahi opencast coal mine

S N	Particulars	Unit	Overburden		Coal	
			Dragline	Shovel	Shovel	Surface Miner
1	Working bench height/ cutting depth	m	27-30	15-18	8-12	0.25-0.35
2	Working bench width	m	75-80	60-66	35-45	60-70
3	Non-working bench width	m	75-80	40	25	60-70
4	Bench slope	Degree	70	70	80	80
5	Blast hole diameter	mm	311	250	160	–
6	Powder factor	kg/m ³	0.6	0.3	0.2	0.0

The parting between Turra and Purewa Bottom seams is being removed by a 24m³/88mR dragline working in a sidecasting mode in the east section. The western section is presently being worked by three draglines, *i.e.*, 20m³/83mR and 20m³/83mR, working in a horizontal tandem. The balance OB above dragline sitting level is being worked by a 20 m³ electric rope shovel working with 120/190 t rear dumpers and a 10 m³ electric rope shovel with 100/120 t rear dumpers.

Two L&T made SM model KSM403 in conjunction with 5.7/6.4 m³ front-end loader and 100/120 t rear dumpers has been deployed to extract Purewa Top and Purewa Bottom. Continuous mining method in windrowing mode is used for SM at NOCM, as shown in Figure 3.4. However, Turra seam is being excavated by 10 m³ electric rope shovel and 11.5 m³ diesel hydraulic shovel working in conjunction with 85/100 t rear dumpers.



Figure 3.4: L&T made KSM403 operating in windrowing mode at NOCM

The cutting speed of SM is ranged between 18 m/min and 22 m/min, with a cutting depth varied from 0.1 m to 0.3 m at different locations of NOCM. It is reduced to 15 m/min in portions with hard bands. In case of SM coal mining, the monthly coal production is ranged between 34916.4 t and 171892.5 t at NOCM. Simultaneously, diesel and picks are lost ranging from 5876.4 l to 18564.4 l and 25 to 112 units in achieving the coal production, respectively. Figure 3.5 shows the time series plot of KSM403 from April 2021 to October 2022 at NOCM. Table 3.5 details the descriptive statistics of monthly availability and utilisation of KSM403.

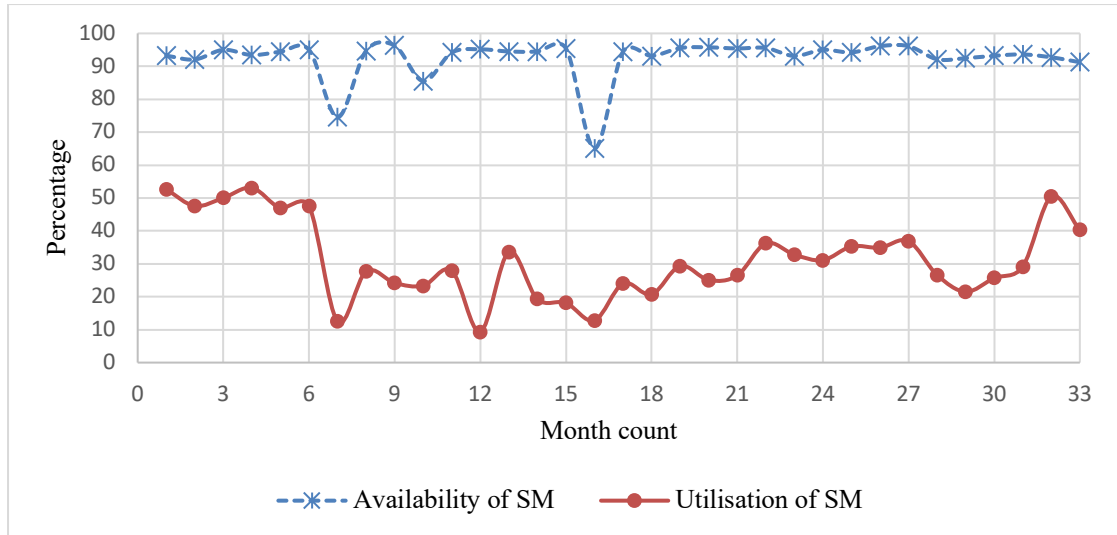


Figure 3.5: Monthly availability and utilisation percentage of KSM403 at NOCM

Table 3.5: Descriptive statistics of availability and utilisation of KSM403 at NOCM

S. No.	Particulars	Availability of SM (%)	Utilisation of SM (%)
1	Mean	92.5	31.3
2	Standard Error	1.1	2.1
3	Standard Deviation	6.3	12
4	Count	33	33

3.2.2 Jayant opencast coal mine

a) Location

Jayant opencast coal mine (JOCM) is situated between latitudes 24°09'50" and 24°11'25" N and longitude 82°38'25" and 82°41'42" E, in the Singrauli district, Madhya Pradesh. It is flanked by Dudhichua and Nigahi projects on the east and west, respectively.

b) Geology

The block area of JOCM is covered by the sediments of the Barakar Formation with a skinny layer of soil and alluvium on top. This formation comprises of fine to coarse grained, light grey, felspathic sandstone, along with carbonaceous shale, clay, shale and coal seams.

The shale bands are present as inter banded with coal to form dirt bands within the seams. The stratigraphic sequence of rocks within this formation is given in table 3.6. The general dip varies from 2° to 4° and it changes from NW to NE. Six faults have been deciphered in the block area of JOCM with the majority traversing through the east section. Figure 3.6 shows the cross-sectional view of JOCM.

Table 3.6: Stratigraphic sequence of rocks within Barakar formation at JOCM

S N	Lithology	Thickness range (m)		Geological reserve (Mt)	Gross calorific value (Kcal/Kg)	Dirt bands (%)
		Min.	Max.			
1	Soil	Nil	12.20			
2	Sandstone with clay and carbonaceous band	16.40	204.90			
3	Coal seam: Purewa Top	4.00	13.07	66.64	2890-4680	24-34.5
4	Sandstone with shale bands	2.80	33.04			
5	Coal seam: Purewa Bottom	8.69	18.54	112.84	3250-5110	11.4-24
6	Sandstone with carbonaceous shale bands	46.61	66.4			
7	Coal seam: Turra	13.9	23.61	188.11	3260-5230	14-23.6



Figure 3.6: Cross-sectional view of Jayant opencast coal mine

c) Mining system

JOCM has been divided into two parts, *i.e.*, east and west sections, each 2.2 km long with a sump as an intersection point. Currently, Purewa Top, Purewa Bottom, and Turra coal seams are under exploitation in the block. OB removal and coal extraction are done using the strip-wise advancing method toward the north. For OB removal, one 24 m³/88R and one 15 m³/83R draglines in the west section, and two units of 24 m³/88R draglines are working in the east section at JOCM. The upper OB benches are proposed to be worked by a 20 m³ electric rope shovel in conjunction with 190 t rear dumpers.

However, coal extraction is being carried out by both, SM and shovel-dumper combination. Turra seam is being extracted by two units of SM model KSM403 operating in continuous method along with the windrowing mode, as shown in Figure 3.7. Extracted coal is loaded by 5.7/6.4 m³ front-end loader onto 100 t rear dumpers. The other two seams are being worked by a 10 m³ electric rope shovel and 9.5 m³ diesel hydraulic shovel working with 100 t rear dumpers.



Figure 3.7: L&T made KSM403 operating in windrowing mode at JOCM

In case of SM coal mining, the working length and width of coal patch is observed approximately 200 m and 70 m on the coal bench, respectively. The cutting speed of SM is ranged between 18 m/min and 22 m/min, with a cutting depth of 0.15 m to 0.2 m at

JOCM. Cutting speed is reduced to 15 m/min in portions with hard bands. The monthly coal production is ranged between 68027 t and 249541.5 t against the diesel loss ranging from 10544.2 l to 25453.2 l and picks loss from 68 to 120 units, simultaneously. Figure 3.8 shows the time series plot of two KSM403 from April 2021 to October 2022 at JOCM. Table 3.7 details descriptive statistics of monthly availability and utilisation of KSM403.

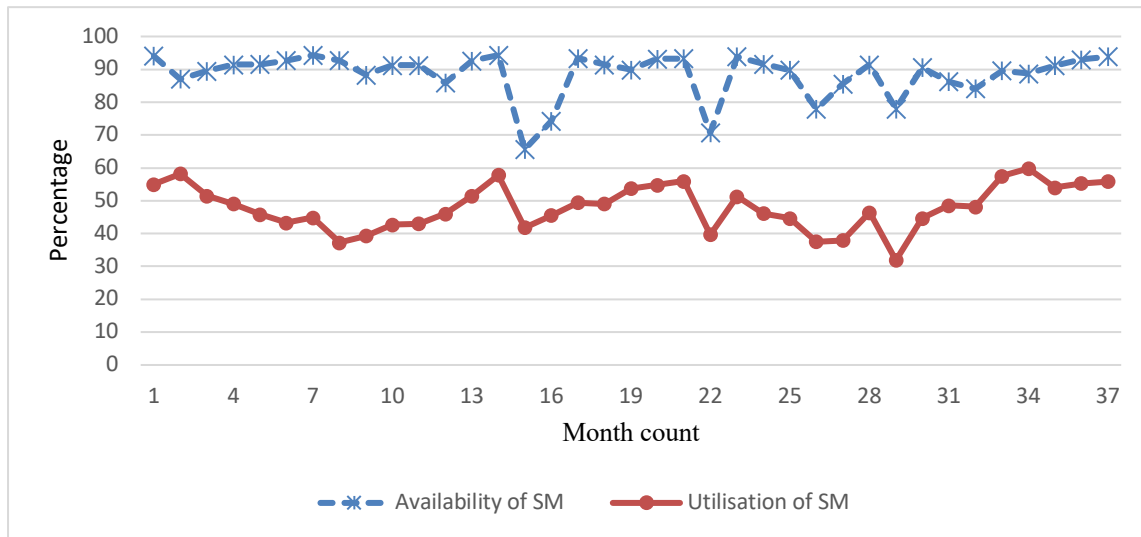


Figure 3.8: Monthly availability and utilisation percentage of KSM403 at JOCM

Table 3.7: Descriptive statistics of availability and utilisation of KSM403 at JOCM

S. N.	Particulars	Availability of SM (%)	Utilisation of SM (%)
1	Mean	88.5	48
2	Standard Error	1.1	1.1
3	Standard Deviation	6.8	6.9
4	Count	37	37

3.2.3 Bhubaneswari opencast coal mine

a) Location

Bhubaneswari opencast coal mine (BOCM) is situated between latitudes 20°57'59''-20°58'43'' (north) and longitudes 85°09'10''-85°11'37'' (east) at Talcher Coalfields, Angul, Odisha, India. It is comprised of an area of 5.8 sq. km in the south-eastern part of

coalfield, surrounded by NH 23 and Sakhigopal block in east, Lingaraj project in south, Ananta expansion project in west, and Arkhapal block in the north.

b) Geology

BOCM holds 374.12 Mt of mineable coal reserves with an overburden of 251.4 Mm³. The mine comprises nine coal seams (Seam I to IX) and one local coal seam (L1). Grade-wise mineable reserves of coal and coal seams occurring within this mining block and their corresponding overburden are tabulated in Table 3.8. The mine contains coal seams interspersed with dirt bands and partings due to faults. Seam IV, for instance, has 13 dirt bands less than 1 m and one dirt band over 1 m in thickness. Seam VIA and VIB are also highly inter-banded. The lithology of dirt bands is composed of fine to coarse-grained sandstone, shale, shaly sandstone, sandy shale, and grey carbonaceous shale. The average gradient of coal seams varies from 1 in 23 to 1 in 8 in the N-NE-E direction.

Table 3.8: Details of coal seams and their corresponding overburden at BOCM

Name of seam	Thickness range (m)	Average thickness (m)	Grade				Coal (Mt) / OB (Mm ³)
			D	E	F	G	
Top OB							118.67
IX	0.42 – 4.24	1.61			0.32		0.32 Mt
Parting	3.20 – 8.33						0.81
VIII	1.40 – 6.70	2.22			0.24	0.25	0.49 Mt
Parting	5.45 – 27.65						3.21
VII	4.00 – 9.04	4.91	1.62	1.25			2.87 Mt
Parting	9.08 – 25.38						5.64
VIB	1.65 – 9.63	5.64				3.73	3.73 Mt
Parting	1.00 – 7.7						1.65
VIA	4.33 – 12.77	8.18			4.00	1.5	5.50 Mt
Parting	1.4 – 30.71						20.29
V	7.15 – 20.84	13.57		3.44	14.09	6.61	24.14 Mt
Parting	3.10 – 11.05						16.85
IV	8.18 – 18.58	10.33	1.15	13.30	19.70	2.88	37.03 Mt
Parting	1.03 – 28.91						13.76
L1			0.74	0.77	0.28	0.79	2.58 Mt
Parting	0.99 – 15.10						19.25
III	9.32 – 19.07	14.55	1.75	33.40	36.04	0.75	71.94 Mt
Parting	0.77 – 14.89						31.60
II	26.86 – 44.9	36.38	3.61	100.1	113.6	8.26	225.52 Mt

c) Mining system

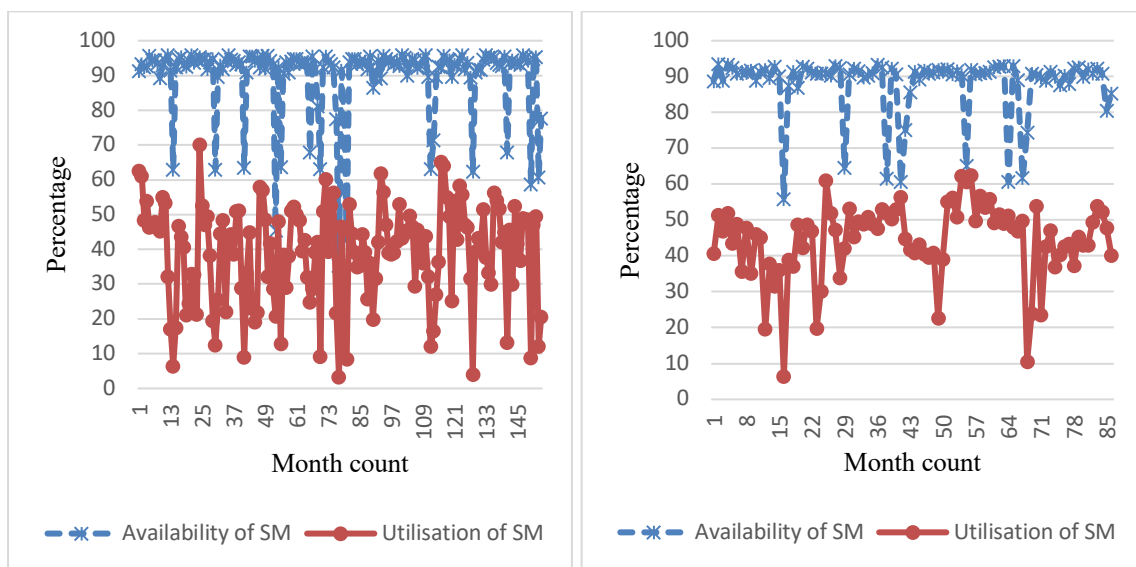
Currently, coal extraction is focused on seams II, III, IV, and V. Seam II occurring above Seam I with an average thickness of 36.38 m, becomes the bottom-most quarriable seam at mine, responsible for 60-70% of mine's total coal production. Mining begins with conventional drilling and blasting to remove overburden. Loose overburden is handled with the help of a shovel-dumper combination. Blast holes of approximately 159 mm are drilled, and explosive slurry cartridges are used. After levelling of coal benches using dozers, Wirtgen made SM models 2200SM3.8 are used to extract 90 m to 180 m long and 50 m to 80 m wide coal benches at BOCM, respectively. Turnback method along with the windrowing mode is used to operate SM, as shown in Figure 3.9. The extracted coal is then rehandled by front-end payloaders to load onto dumpers.



Figure 3.9: Wirtgen made 2200 SM 3.8 in conjunction with front-end payloaders at BOCM

The cutting speed of SM is varied between 10 m/min and 22 m/min, with a cutting depth ranged from 0.15 m to 0.35 m at different locations of BOCM. It is reduced up to 5

m/min in portions with hard bands. In case of SM coal mining, the monthly coal production is ranged between 41580 t and 317116.8 t at BOCM. Simultaneously, diesel and picks are lost ranging from 8149.7 l to 22262.5 l and 42 to 132 units in achieving the coal production, respectively. Figure 3.10 (a) and (b) shows the time series plot of five 2200SM3.8 for cutting depths 0.25 m and 0.35 m, from October 2018 to January 2022 at BOCM, respectively. Table 3.9 details the descriptive statistics of monthly availability and utilisation percentage of 2200SM3.8 models at BOCM.



(a)

(b)

Figure 3.10: Monthly availability and utilisation percentage of 2200SM3.8 at BOCM: **a)** at cutting depth as 0.25 m; **b)** at cutting depth as 0.35 m

Table 3.9: Descriptive statistics of availability and utilisation of 2200SM3.8 at BOCM

Particulars	Availability of SM (%)		Utilisation of SM (%)	
	Cutting depth as 0.25 m	Cutting depth as 0.35 m	Cutting depth as 0.25 m	Cutting depth as 0.35 m
Mean	89.84	88	39	44.5
Standard Error	0.88	0.92	1.15	1.14
Standard Deviation	10.87	8.6	14.33	10.54
Count	154	86	154	86

3.2.4 Rajmahal opencast coal mine

a) Location

Rajmahal opencast coal mine (ROCM) is situated in Godda, Jharkhand, between the latitudes 25°1'12" and 25°3'15" N and longitudes 87°21'0" and 87°24'0" E. This mine is located within the Lalmatia Exploration Block, encompassing 15 Km² in the northernmost part of the Hura coal basin.

b) Geology

Rajmahal Coalfield consists of a group of geological blocks. Despite their separation, these blocks exhibit signs of geological continuity. Seventeen normal faults have been deciphered within the block, out of which five southward heading faults, namely Faults F1, F6, F8, F11 and F15 are of significant magnitude. It leads to a more complex structure in the southern half of the block.

The Lalmatia block area is covered by the sediments of the Barakar formation from the Lower Gondwana group. It consists of medium to coarse grained sandstone, shale, carbonaceous shale and coal. Eight highly inter-banded coal seams have been identified within the block, *i.e.*, seams I, II (Bottom), II (Top), III, IV, IX, X and XI in ascending order. The seams II (Bottom), II (Top) and III merge and split frequently to form various combinations. Coal seams consist of a dip of usually 2° to 3° due East within the area. Seams of the upper horizon occur mainly in the south of fault F-8, where up to 10° dip is observed in the vicinity of structural disturbances. Seams II (Bottom), II (Top) and III comprise around 95% of the block's geological coal reserve with their various combinations. Table 3.10 details the sequence of coal seams in ROCM.

Table 3.10: Sequence of coal seam and OB / parting at ROCM

S. N.	Coal seam and overburden / parting	Thickness range (m)		Geological coal reserve (Mt)/OB (Mm ³)
		Minimum	Maximum	
1.	Top OB	15	90	266.58
2.	Seams-IV and upper seams	0.5	6	7.8
3.	Intervening parting among upper seams	1	25	33
4.	Seam-III	5	10	22.8
5.	Parting between Seam-III and Seam-II (Top)/ II (Combined)	1	44	72.88
6.	Seam-II (Top)	7	13	69.47
7.	Parting between seam-II (top) and II (bottom)	1	26.50	24.26
8.	Seam-II (Bottom / Combined)	10 / 24	16 / 36	85.43

c) Mining system

ROCM has been divided into three mining zones, *i.e.*, main mining zone, deep mining zone and Lohandia Mouza area. The deep mining zone is present in the south of fault F8, whereas the Lohandia area lies in the north of the pit and beyond the existing pit limit. Meanwhile, most of the reserves are concentrated in the main mining zone. Top overburden of mining zone is removed by 12 m³ hydraulic shovels in conjunction with 100 t dumpers. The parting between seam-II (Bottom) and seam-II (Top) and the parting between seam-II (Top) and seam-III are being removed using 10 m³ electric rope shovel and 100 t rear dumpers. 20 m³ electric rope shovel in conjunction with 170 t or 190 t upgraded electric wheel dumpers are deployed to remove the remaining OB. However, SM combined with 10 m³ front-end loader and 100 t dumpers are used to extract coal. It is also being done by 12 m³ hydraulic shovels in conjunction with 100 t dumpers.

Wirtgen made SM model 2200 SM 3.8 is deployed on seams III, II (Top), and II (Bottom) with a coal patch of 100 m to 160 m in length and 60 m to 90 m in width at ROCM, respectively. Turnback method with windrowing is used during coal cutting. The

cutting speed of SM is varied between 12 m/min and 20 m/min, with a cutting depth ranged from 0.15 m to 0.30 m at different locations of ROCM. In case of SM coal mining, the monthly coal production is ranged between 40614 t and 271656 t at ROCM. Simultaneously, diesel and picks are lost ranging from 6904.4 l to 23090.8 l and 30 to 120 units in achieving the coal production, respectively. Figure 3.11 (a) and (b) shows the time series plot of one SM for a cutting depth of 0.25 m and two SM for 0.30 m, from Jun 2017 to April 2019 at ROCM, respectively. Table 3.11 details descriptive statistics of monthly availability and utilisation of 2200SM3.8 at ROCM.

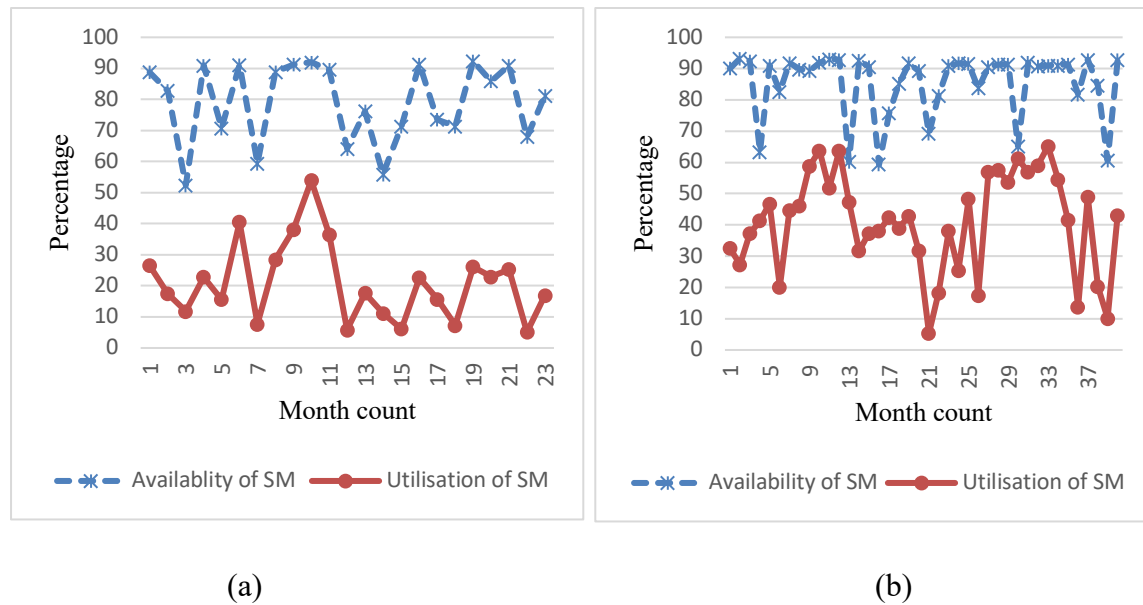


Figure 3.11: Monthly availability and utilisation percentage of 2200SM3.8 at ROCM: **a)** at cutting depth as 0.25 m; **b)** at cutting depth as 0.30 m

Table 3.11: Descriptive statistics of availability and utilisation of 2200SM3.8 at ROCM

Particulars	Availability of SM (%)		Utilisation of SM (%)	
	Cutting depth as 0.25 m	Cutting depth as 0.30 m	Cutting depth as 0.25 m	Cutting depth as 0.30 m
Mean	79.1	85.5	21	41
Standard Error	2.7	1.6	2.6	2.5
Standard Deviation	12.9	10.4	12.6	15.8
Count	23	40	23	40

3.2.5 Parsa East and Kanta Basan opencast coal mine

a) Location

Parsa East and Kanta Basan opencast coal mine (PEKB) is situated between latitudes 22°48'57" and 22°51'57" N and longitudes 82°45'10.50" and 82°47'22" E in the north-central region of the Hasdeo-Arand coalfields, Surguja, Chhattisgarh, India. It is distinguished as a densely forested area rich in biodiversity.

b) Geology

PEKB lies within the Parsa East and Kanta Basan coal block, which covers an area of about 27.67 Km² in the northernmost part of Hasdeo coal basin. The block is located next to Parsa coal block, followed by Kente Extension coal block in the northern side. PEKB coal block is overlain by sediments from the Barakar formation, dating back to the Lower Permian age. This formation is composed of fine to coarse-grained sandstone, shale, sandy shale, carbonaceous shale, shaly coal and coal seams. Table 3.12 lists the coal seams, namely, II, IV, V, and VI in ascending order at PEKB with their total geological reserves.

Table 3.12: Sequence of coal seam and parting at PEKB opencast mine

Seam / Parting	Thickness (m)		General thickness (m)		GCV (Kcal/Kg)		Grade		Geological reserves (Mt)
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	
VI	0.66	2.5	1.2	2	2658	4637	G16	G9	40.71
Parting	9.71	23.1	15	20					
V	1.41	8.37	2	7	2465	3815	G17	G12	141.88
Parting	17.98	31.75	18	22					
IV	5.2	10.07	7	8.5	3686	5526	G13	G8	282.17
Parting	48.62	55.61	49	53					
II	0.62	0.75	0.65	0.7	2765	3875	G16	G12	8.75

Highly interbanded coal horizons of the Barakar formation have been identified in the block due to the presence of normal faults within the block. Over 95% of the block's reserves are found in seams IV, V, and VI, with the floor of seam IV forming the base of the mine. All coal seams consist of a gentle 2^0 to 3^0 dip towards the East was observed.

c) Mining system

Top overburden is removed by hydraulic shovels in conjunction with 100 t dumpers. The parting between seams IV and V and between seams V and VI is being removed by a 20 m³ electric rope shovel combined with 100 t rear dumpers and 190 t upgraded electric wheel dumpers. Coal extraction is carried out using Wirtgen made 2200 SM 3.8 in conjunction with 5 m³ front-end loader and 100 t dumpers on seams IV, V and VI at PEKB. Turnback method along with the windrowing mode is used to operate SM, as shown in Figure 3.12. The working length and width of a coal patch varied from 90 m to 175 m and 40 m to 70 m, respectively.



Figure 3.12: Wirtgen made 2200 SM 3.8 deployed at PEKB

The cutting speed of SM is varied between 10 m/min and 25 m/min, with a cutting depth ranged from 0.13 m to 0.30 m at different locations of PEKB. In case of SM coal mining, the monthly coal production is ranged between 22377.6 t and 368971.2 t at PEKB.

Simultaneously, diesel and picks are lost ranging from 4251.7 l to 27672.8 l and 20 to 144 units in achieving the coal production, respectively. Figure 3.13 shows the time series plot of a 2200 SM 3.8 from April 2019 to March 2020 at PEKB. Table 3.13 details descriptive statistics of monthly availability and utilisation of 2200 SM 3.8 at PEKB.

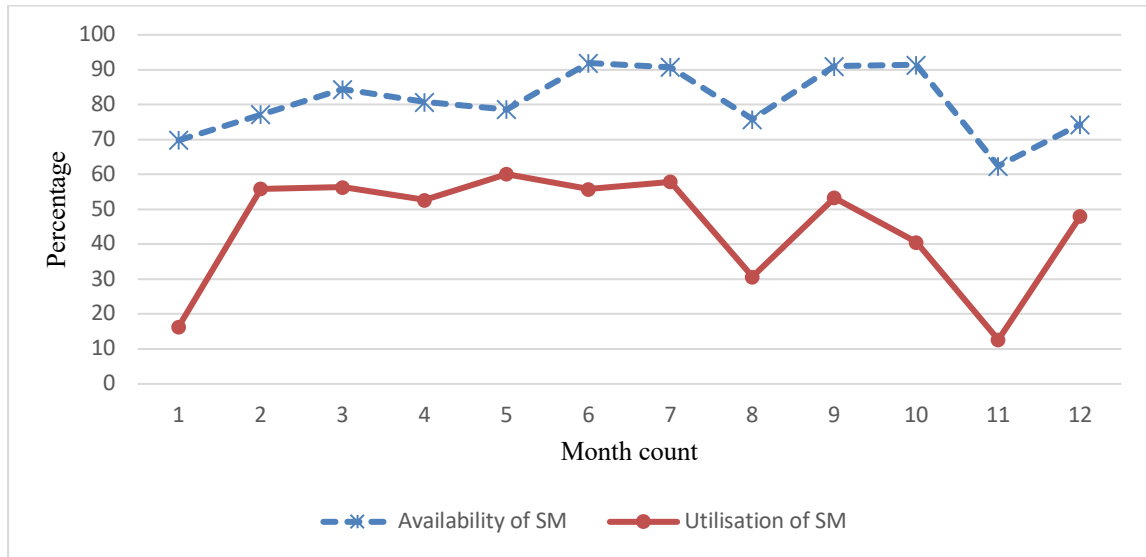


Figure 3.13: Monthly availability and utilisation percentage of 2200 SM 3.8 at PEKB

Table 3.13: Description of availability and utilisation percentage of 2200 SM 3.8 at PEKB

S. N.	Particulars	Availability of SM (%)	Utilisation of SM (%)
1	Mean	80.7	45
2	Standard Error	2.7	4.7
3	Standard Deviation	9.5	16.5
4	Count	12	12

3.2.6 Samaleswari opencast coal mine

a) Location

Samaleswari opencast coal mine (SOCM) is situated in the Ib Valley coalfields, towards the west of Hingir Rampur colliery, Jharsuguda, Odisha, India. It is positioned within latitudes 21°46'48" and 21°49'22" North and longitudes 83°52'23" and 83°56'00" East.

b) Geology

The Samaleswari & Kudopali (Comb.) block is positioned in the southern region of Ib Valley coalfields. The stratigraphy of the Ib Valley coalfield consists of thick sediments from the Lower Gondwana group. The Kamthi formation related to this group has been divided into lower, middle, and upper sub-sections. The lower section is correlated with the Barren Measures, the middle section with Raniganj and the upper section with Kamthi. It is represented by gently rolling undulating topography with softer formations like coal seams with carbonaceous and grey shales, forming linear depressions and occupied by pebble beds and relatively harder sandstones. The block is traversed by nine faults, and F1 to F3 and F5 to F7 are throwing toward the north, and F8 to F10 are throwing toward the south. The strike of formation in the block generally exhibits NE-SW, and the dip generally goes towards N-W. The minimum and maximum dip amount ranges between less than 1° and around 8°, respectively. However, the general dip varied from 3° to 5°.

Samaleswari and Kudopali (Comb.) block covers an area of 19.57 km² and three coal seams, viz., Lajkura seam, Rampur seam and Ib seam. Altogether seventeen coal seams occur in the SOCM area., viz., Parkhani, Local 6, Local 5, Local 4, Local 3, Local 2, Lajkura, Local 1, Rampur A (Top), Rampur A (Bottom), Rampur B (Top), Rampur B (Bottom), Rampur C (Top), Rampur C (Bottom), Rampur D+E, Rampur F of the Barakar Formation and seam IB of the Karharbari Formation in descending order are considered for reserve estimation, *i.e.*, 0.47 Mt, 1.238 Mt, 15.489 Mt, 11.295 Mt, 10.774 Mt, 8.395 Mt, 260.331 Mt, 14.47 Mt, 72.617 Mt, 61.131 Mt, 32.621 Mt, 86.9 Mt, 47.751 Mt, 55.73 Mt, 151.933 Mt, 13.291 Mt, 22.675 Mt, respectively. The Rampur seam intersected about 90m below the Lajkura seam. Therefore, Rampur and Ib seams below Lajkura seam are not considered mineable. Currently, coal from the Lajkura seam, having a thickness of 12.7 m to 27.18 m, is mined in SOCM.

c) Mining system

Top-soil is removed and stacked either in temporary storage areas or directly transported to backfilled areas and levelled for reclamation. Overburden benches are aligned along the strike, with 10 m to 12 m of maximum bench height and 22 m to 32 m of bench width. Overburden is being excavated by 5 m³ electric rope shovels and 9.5 m³ diesel hydraulic shovels in conjunction with 100 t and 50 t rear dumpers using level slicing method. Parting is being excavated exclusively by a diesel hydraulic shovel of 2.5 m³ capacity in conjunction with 50 t dumpers. Coal benches is being kept at a minimum width of 50 m along with approximately 100 m long and levelled coal patches for coal extraction. Coal of (-)100 mm size is being extracted on the Lajkura seam using L&T made SM model KSM 303 in conjunction with 5-6 m³ front-end loader and 35 t rear dumpers combination. Turnback method in windrowing mode is used for SM at SOCM, as shown in Figure 3.14.



Figure 3.14: Coal extraction by L&T made KSM 303 at SOCM

The cutting speed of SM is ranged between 14 m/min and 21 m/min, with a cutting depth varied from 0.15 m to 0.3 m at different locations of SOCM. In case of SM coal mining, the monthly coal production is ranged between 48384 t and 180682.3 t at

SOCM. Simultaneously, diesel and picks are lost ranging from 10450.9 l to 21139.8 l and 46 to 108 units during this coal production, respectively. Figure 3.15 shows the time series plot of KSM 303 from April 2015 to March 2017. Table 3.14 details descriptive statistics of monthly availability and utilisation of KSM 303 at SOCM.

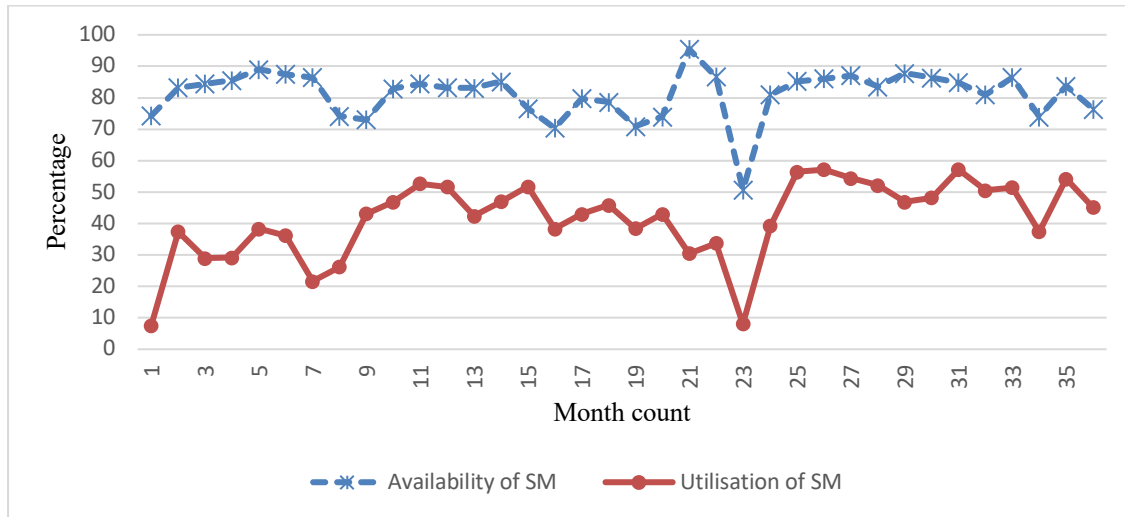


Figure 3.15: Monthly availability and utilisation percentage of KSM303 at SOCM

Table 3.14: Descriptive statistics of availability and utilisation of KSM303 at SOCM

S. N.	Particulars	Availability of SM (%)	Utilisation of SM (%)
1	Mean	81.2	41.4
2	Standard Error	1.3	2.1
3	Standard Deviation	7.8	12.4
4	Count	36	36

3.2.7 Lakhanpur opencast coal mine

a) Location

Lakhanpur opencast coal mine (LOCM) is situated between latitudes 21°43'12" and 21°47'32" North and longitudes 83°47'59" and 83°51'30" East within the Belpahar-III geological block of Rampur tract of the Ib Valley coalfield, positioned south of Lilari nallah.

b) Geology

The Belpahar-III geological block contains three primary coal seams, viz., Ib, Rampur and Lajkura seams. The Lajkura seam is present as a compact seam covering an area of 22.40 km², while the Rampur and Ib seams are divided into multiple splits. The thickness of coal seams and intervening partings are given in Table 3.15. The dip of the strata ranges from 4° to 6°, trending NW on the northern side and WSW on the southern side. The block is intersected by eight normal faults. However, two faults with a throw ranging from 2 m to 5 m are present within the mining block.

The mining block contains Lajkura seam as a single mineable coal seam across the entire block, having a gradient of 3.7° to 5° with total proved geological reserve of 674.81 Mt. The average thickness of the Lajkura seam is 24.04 m, with intermediate varying parting and 1 to 4 number of dirt bands having an average thickness of 3.56 m.

Table 3.15: Sequence of coal seam and parting of Belpahar-III geological block

S. N.	Seam / Section	Thickness (m)		Parting with the lower seam (m)	
		Minimum	Maximum	Minimum	Maximum
1	Belpahar	1.49	4.20	68.16	72.67
2	Parkhani	0.20	5.18	75.28	110.52
3	Lajkura	20.88	33.53	41.65	96.22
4	Section-A (Rampur Top - I)	0.35	3.75	0.45	10.10
5	Section-B (Top) (Rampur Top - II)	0.18	3.83	0.31	3.12
6	Section-B (Bottom) (Rampur Top - II)	0.12	2.59	1.28	24.93
7	Section-C	0.12	3.83	3.98	12.56
8	Section-D (Rampur Bottom-I part)	0.11	2.44	2.61	18.43
9	Section-E (Rampur Bottom-II part)	0.62	5.45	5.85	35.55
10	Ib (Top)	0.09	6.20	0.80	9.58
11	Ib (Bottom) Ib (Combined)	0.15 4.42	8.00 10.95	-	-

c) Mining system

Overburden is being removed using a shovel dumper combination at LOCM. Top overburden is removed by 2.5 m³ and 3.7 m³ electric hydraulic shovels combined with 50 t rear dumpers. The parting is being removed by a 5 m³ and 5.1 m³ electric rope shovel combined with 50 t rear dumpers. Coal mining is being done using SM in conjunction with 5 m³ front-end loaders and 50 t and 35 t rear dumpers at LOCM. The L&T made SM model KSM303 is deployed on the Lajkura seam operating in a turnback method with windrowing mode on a wide coal bench at LOCM. The length and width of the working coal patch is varied from 130 m to 150 m and 60 m to 90 m, respectively.

The cutting speed of SM is ranged between 15 m/min and 22 m/min, with a cutting depth varied from 0.15 m to 0.21 m at different locations of LOCM. In case of SM coal mining, the monthly coal production is ranged between 85449.6 t and 215119.8 t at LOCM. Simultaneously, diesel and picks are lost ranging from 12646.5 l to 23232.9 l and 64 to 110 units during this coal production, respectively. Figure 3.16 shows the plot of the time series plot of KSM 303 from April 2015 to March 2017. Table 3.16 details descriptive statistics of monthly availability and utilisation of KSM 303 at LOCM.

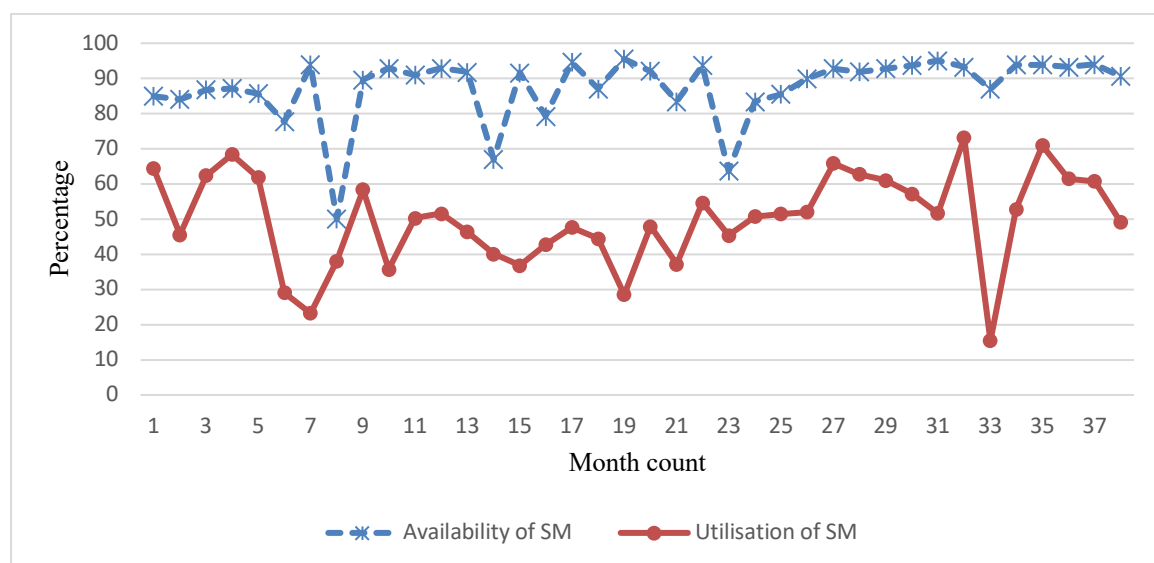


Figure 3.16: Monthly availability and utilisation percentage of KSM303 at LOCM

Table 3.16: Descriptive statistics of availability and utilisation of KSM303 at LOCM

S. N.	Particulars	Availability of SM (%)	Utilisation of SM (%)
1	Mean	87.5	49.9
2	Standard Error	1.5	2.2
3	Standard Deviation	9.5	13.2
4	Count	38	38

3.2.8 Gevra opencast coal mine

a) Location

Gevra opencast coal mine (GOCM) is situated in the south-central region of Korba coalfield, Chhattisgarh, India. Its location lies in between latitudes 22°18'00" and 22°21'42" North and longitudes 82°32'00" and 82°39'30" East. The area features a gently undulating terrain with elevations ranging from 288 m to 328 m above MSL.

b) Geology

The stratigraphic succession of Gevra block is overlaid with a layer of soil, typically ranging from 3 m to 6 m thick. This coal block is overlain by sediments from the Barakar formation, dating back to the Lower Permian age. This formation is divided into Upper Barakar and Middle Barakar, which are composed of fine to coarse-grained sandstone, shale, sandy shale, carbonaceous shale, shaly coal and thick coal seams. Highly interbanded coal horizons of the Barakar formation have been identified in the block due to the presence of normal faults within the block. This block has been divided into three parts, namely, western part, eastern part and central part with a gradient of 3° to 4° towards south, 2° to 6° towards NE to SE and 4° to 6° towards south to SE, respectively. The presence of four coal seams is observed in the block, namely, D, E&F, Upper Kusmunda and Lower Kusmunda in descending order. Meanwhile, Lower Kusmunda seam occurs in two

sections, namely, Lower Kusmunda (Top section) and Lower Kusmunda (Bottom section), in a major part of the block. Table 3.17 summarises the sequence of coal seams and partings in Gevra block.

Table 3.17: Sequence of coal seam and parting within the Gevra block

Coal seam / Overburden	Thickness (m)		Parting with the lower seam (m)		Mineable reserve (Mt)	Inseam band (Mm ³)
	Min.	Max.	Min.	Max.		
Overburden					594.9Mm ³	
D	1.10	25.32	63.74	102.79	54.2	1.35
E&F	9.25	16.70	13.26	65.46	107.66	5.36
Upper Kusmunda	21.00	36.50	36.60	83.89	388.13	24.95
Lower Kusmunda (Top section)	19.28	45.23	2.69	23.91	727.03	26.34
Lower Kusmunda (Bottom section)	3.14	16.16			59.68	2.60

c) Mining system

Overburden is being removed by shovel dumper combination. It is removed by a 42 m³ electric rope shovel in tandem with 240 t rear dumpers, a 15 m³ electric hydraulic shovel in tandem with 120 t rear dumpers and a 10 m³ electric hydraulic backhoe in tandem with 100 t rear dumpers. Coal extraction is carried out using SM combined with 10 m³ front-end loader and 60 t rear dumpers in GOCM. The Wirtgen made SM model 2200 SM, and 2200 SM 3.8 and L&T made SM model KSM 304 are deployed on lower and upper Kusmunda seams. The length and width of the working coal patch is varied between 80 m to 160 m and 60 m to 80 m, respectively. Figure 3.17 shows KSM 304 operating in a turnback method along with a windrowing mode at GOCM.



Figure 3.17: Coal production by L&T made KSM 304 at Gevra opencast coal mine

The cutting speed of SM is ranged between 12 m/min and 25 m/min, with a cutting depth varied from 0.15 m to 0.28 m at different locations of GOCM. In case of SM coal mining, the monthly coal production is ranged between 33805.35 t and 262008 t at GOCM. Simultaneously, diesel and picks are lost ranging from 5408.9 l to 23056.7 l and 31 to 121 units during this coal production, respectively. Figure 3.18 shows the time series plot of the SM from April 2017 to March 2019 at GOCM. Table 3.18 details descriptive statistics of monthly availability and utilisation of 2200 SM, 2200 SM 3.8, and KSM304 at GOCM.

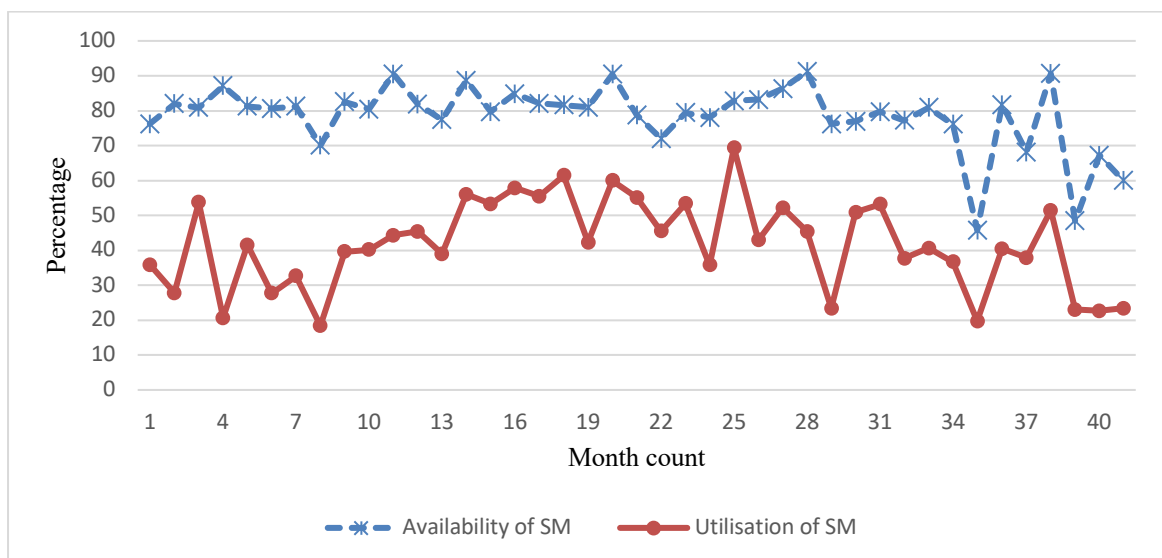


Figure 3.18: Monthly basis availability and utilisation percentage of SM at GOCM

Table 3.18: Descriptive statistics of availability and utilisation of SM at GOCM

S. N.	Particulars	Availability of SM (%)	Utilisation of SM (%)
1	Mean	78.6	41.8
2	Standard Error	1.5	2.0
3	Standard Deviation	9.6	12.9
4	Count	41	41

3.3 Laboratory investigations for coal parameter

The measurement of coal parameter is necessary for investigating the total factor productivity of SM in opencast coal mines. Different number of locations were selected for collecting coal samples based on the number of SM operating in different conditions at different locations in an opencast coal mine. Coal samples were collected from each selected location for laboratory investigations. Uniaxial compressive strength, tensile strength, ash content, and moisture content were measured for characterising the collected coal samples. Methods followed in these tests are described as follows:

3.3.1 Uniaxial compressive strength

Uniaxial compressive strength is used to measure the strength of a coal sample under uniaxial compression using a specimen with a regular geometry (ISRM, 1972). Test specimens without surface irregularities are prepared by cutting them with a diamond saw, utilising water as coolant. These specimens are kept at room temperature for approximately five days before testing to remove the moisture introduced during cutting. Test specimens are meticulously prepared to meet the tolerances outlined by the International Society for Rock Mechanics Commission on Standardisation of Laboratory and Field Tests.

Test specimens are prepared as in right circular cylindrical shape with a height-to-diameter ratio of 2.5-3.0 and a diameter of approximately 54 mm. A constant stress rate is applied continuously to the specimen, ensuring failure occurs within 5 to 10 minutes of

loading along the core axis in a hydraulic stiff compression testing machine to measure the failure load. The uniaxial compressive strength of the specimen was calculated using Equation 3.1. Table 3.19 details the descriptive statistics of uniaxial compressive strength in Indian opencast mines.

$$\sigma_c = \frac{4F}{\pi d^2} \quad (\text{Equation 3.1})$$

where, σ_c is the uniaxial compressive strength (MPa), d is the diameter of specimen (mm), F is the load at failure (N).

Table 3.19: Descriptive statistics of uniaxial compressive strength for collected samples

S. N.	Opencast coal mine	Count	Minimum	Maximum	Mean	Range	Standard error	Standard deviation
1.	Nigahi	10	8.8	39.46	25.3	30.66	3.3	10.5
2.	Jayant	6	13.2	38	24.3	24.8	4.0	9.9
3.	Bhubaneswari	10	10.2	39.4	23.8	29.2	3.5	11.3
4.	Rajmahal	8	9.34	35.8	20.9	26.46	3.5	9.9
5.	Parsa East and Kanta Basan	10	8.92	32.42	19.4	23.5	2.8	8.97
6.	Samaleswari	6	9.71	39.76	23.4	30.0	4.1	10.2
7.	Lakhanpur	6	13.24	33.67	22.5	20.43	2.9	7.2
8.	Gevra	13	11.11	35.8	22.63	24.69	1.8	6.7

3.3.2 Tensile strength

Tensile strength is used to assess the strength of a coal sample under tension using a specimen with a regular geometry (ISRM, 1977). The specimen diameter is kept at approximately 54 mm, with its thickness roughly equal to its radius. A continuous load is applied to the specimen at a constant rate, ensuring failure occurs in the weakest zone within 15-30 seconds. Tensile strength of coal was determined using Equation 3.2. Table 3.20 describes the statistics of coal tensile strength in Indian opencast mines.

$$\sigma_t = \frac{2F}{\pi dt} \quad (\text{Equation 3.2})$$

where, σ_t is the Brazilian tensile strength (MPa), F is the load at failure (N), d is the diameter of specimen (mm), t is the thickness of specimen (mm).

Table 3.20: Descriptive statistics of tensile strength for collected samples

S. N.	Opencast coal mine	Count	Minimum	Maximum	Mean	Range	Standard error	Standard deviation
1.	Nigahi	10	0.7	4	2.6	3.3	0.31	0.99
2.	Jayant	6	1.4	4	2.5	2.6	0.38	0.95
3.	Bhubaneswari	10	0.9	3.73	2.1	2.8	0.32	1.0
4.	Rajmahal	8	0.55	3.2	1.6	2.65	0.34	0.95
5.	Parsa East and Kanta Basan	10	0.91	3.5	2.2	2.59	0.27	0.85
6.	Samaleswari	6	1.5	2.5	2.1	1	0.19	0.46
7.	Lakhanpur	6	0.95	2.74	1.7	1.79	0.26	0.65
8.	Gevra	13	1.35	3.74	2.6	2.39	0.23	0.82

3.3.3 Moisture content

Moisture in coal exists in different possible forms. Adventitious moisture, which is present in coal due to groundwater and other external sources evaporates quickly. In contrast, the moisture contained within the coal, known as inherent moisture, is assessed quantitatively (Parikh *et al.*, 2005). Test specimens are gathered to measure the moisture content from various locations related to SM working coal benches using a channel sampling technique. This technique follows the cutting of a section with dimensions of 30 cm wide and 10 cm deep, representing the total cross-section (top to floor) of a seam (IS, 1965).

Afterwards, these test specimens are ground, crushed and pulverised through the grinder, jaw crusher, roll crusher and pulveriser, respectively. Pulverised test specimens consist mainly of particles having a diameter of (-) 212 microns. Multiphase coning and

quartering were done while these specimens were being prepared. Then, it is stored in air-tight polybags to avoid further oxidation and contamination.

Before conducting any laboratory tests, 20 g to 30 g of pulverised coal is taken out from polybags and dispersed in a 1000 cm² tray at lab temperature and humidity for 24 hours. The moisture content of a pulverised coal specimen is determined by placing 1 g of air-dried coal sample in a petri dish, as given in Figure 3.19a. Next, the sample, along with the lid, is placed in an electric hot air oven at 108° C for 1 hour, as shown in Figure 3.19b.

The sample is then cooled to room temperature in a desiccator for around 20 minutes before being weighed again. Equation 3.3 outlines the weight loss, expressed as a percentage, representing moisture content in a pulverised test specimen (IS, 1984). Table 3.21 describes the statistics of moisture content for collected samples.

$$MC = \frac{(W_2 - W_3) \times 100}{(W_2 - W_1)} \quad (\text{Equation 3.3})$$

where, MC is the moisture content (%), W₁ is the empty petri dish weight (g), W₂ is the coal sample weight with petri dish before heating (g), W₃ is the coal sample weight with petri dish after heating (g).



(a)



(b)

Figure 3.19: Measurement of moisture content: **a)** Weighted coal samples; **b)** hot air oven

Table 3.21: Descriptive statistics of moisture content for collected samples

S. N.	Opencast coal mine	Count	Minimum	Maximum	Mean	Range	Standard error	Standard deviation
1	Nigahi	10	5.2	10.3	8.1	5.1	0.59	1.9
2	Jayant	6	5	8.4	6.6	3.4	0.58	1.4
3	Bhubaneswari	10	4	8.8	5.13	4.8	0.46	1.5
4	Rajmahal	8	5.6	8.8	7.1	3.2	0.33	0.9
5	Parsa East and Kanta Basan	10	1.5	5.9	3.9	4.4	0.47	1.5
6	Samaleswari	6	7.3	11.7	9.13	4.4	0.7	1.7
7	Lakhanpur	6	3.7	11.8	8.85	8.1	1	3.1
8	Gevra	13	3	9	6.0	6.0	0.5	1.8

3.3.4 Ash content

The non-combustible residue remaining after coal combustion is known as the ash content of coal. It reflects the net amount of minerals present in different proportions after expelling carbon, oxygen, sulphur, and water (including clays) during combustion. Ash content of a pulverised test specimen is measured by placing freshly crushed 1 g of air-dried coal sample in a covered crucible having a diameter of (-) 212 microns, as shown in Figure 3.20a. The specimen is heated in a muffle furnace at 810° C for 1 hour, as illustrated in Figure 3.20b. Then the silica crucible is moved out from furnace to desiccator, as shown in Figure 3.20c. Lastly, Equation 3.4 outlines the weight of residue in crucible to assess the ash content of a test specimen (IS, 1984). Table 3.22 details statistics of ash content for collected samples.

$$AC = \frac{(W_3 - W_4) \times 100}{(W_2 - W_1)} \quad (\text{Equation 3.4})$$

where, AC is the ash content (%), W_1 is the empty crucible weight before heating (g), W_2 is the coal sample weight with crucible before heating (g), W_3 is the coal residue weight with crucible after heating (g), W_4 is the crucible weight after heating (g).



(a)

(b)

(c)

Figure 3.20: Measurement of ash content: **a)** weighted coal sample before heating; **b)** muffle furnace; **c)** coal residue after heating

Table 3.22: Descriptive statistics of ash content for collected samples

S. N.	Opencast coal mine	Count	Minimum	Maximum	Mean	Range	Standard error	Standard deviation
1	Nigahi	10	26.1	54.4	37.96	28.3	3.1	9.9
2	Jayant	6	21.32	52.3	37.3	30.98	4.8	11.8
3	Bhubaneswari	10	28.8	55.8	37.85	27	2.6	8.2
4	Rajmahal	8	23.5	58	37.4	34.5	4.0	11.4
5	Parsa East and Kanta Basan	10	22.8	53.7	35.35	30.9	3.0	9.6
6	Samaleswari	6	25.9	57.2	42.4	31.3	4.9	12.0
7	Lakhanpur	6	28.1	50.7	36.75	22.6	3.4	8.3
8	Gevra	13	22.4	56.8	31.95	34.4	2.7	10.0

3.4 Field investigations for machine parameter

The factors related to machine productivity, namely, cutting width, rated power for cutting drum, cutting depth, cutting area, cutting speed and drum speed were measured to investigate their influence on key productivity indicators of SM in opencast coal mines.

3.4.1 Cutting width

Center to center distance between two adjacent cuts of SM was measured to measure the cutting width of SM during coal cutting, as illustrated in Figure 3.21. Cutting width of SM was consistent during the entire length of working face for coal mining.



Figure 3.21: Measurement of center to center spacing between two adjacent cuts of SM

3.4.2 Rated power for cutting drum

Various components within the SM require power distribution for proper operation. The actual power transmitted to the cutting drum from the machine's rated power working in a windrowing mode during coal cutting is calculated by subtracting the sum of powers utilised by different components, namely, crawler drive, cooling fan, water system, cylinder, gear, and air conditioner. A schematic diagram of power transmission arrangement is illustrated in Figure 3.22.

The rated power of SM was estimated using a machine manual. The power allocated to the cutting drum is 83% of the rated machine power (Kumar *et al.*, 2018). Power losses in belt drives system from speed and torque losses (Belta *et al.*, 2015). A study found that power transmission efficiency in V-belts can decrease by over 20% due to wear and operational degradation (RPTS, 2015). Finally, 20% more power is lost due to slippage between the pulley and belt. Thus, the power transfer ratio to the cutting drum was estimated as 0.66 for the middle cutting drum-type SM (Kumar *et al.*, 2018).

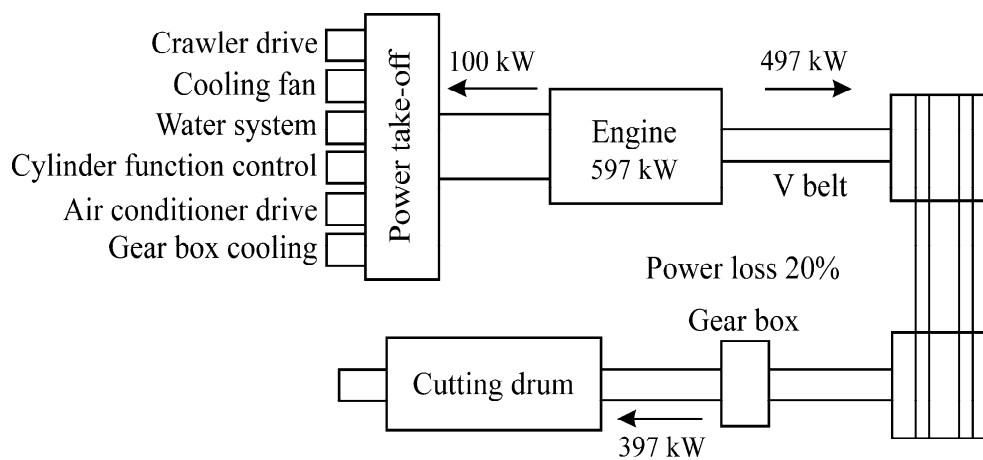


Figure 3.22: Schematic diagram of power transmission arrangement for SM

3.4.3 Cutting depth

Cutting depth depends on the machine's specifications like rated power and cutting drum's diameter and coal seam properties. During the field study, small berms were observed because of the cutting process by SM on the vertical section of the coal seam. These berms typically represent the cutting depth achieved by the cutting drum at different time intervals. The cutting depth was measured by a steel scale. Figure 3.23 (a) represents the front view of the coal bench slope, and Figure 3.23 (b) depicts the conceptual sectional view of the cutting process.



Figure 3.23: Measurement of SM cutting depth at BOCM: **a)** front view of coal bench slope; **b)** sectional view of coal bench

3.4.4 Cutting area

During pick-coal interaction, a segment of cutting drum of SM contacts the coal. Figure 3.24 depicts a schematic diagram of the cutting drum during coal mining.

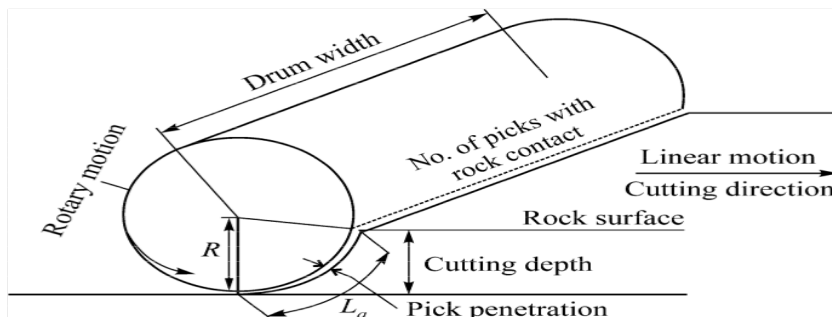


Figure 3.24: Length of arc of drum in contact with coal during coal cutting operation

The arc length in contact with coal during coal cutting was determined by the radius of the cutting drum and the cutting depth, as shown in Equation 3.5. Area of cutting drum in contact with coal during cutting operation depends on the length of arc of drum in contact with coal and width of the cutting drum, as given in Equation 3.6. These relationships are valid only for the cutting depths less than the cutting drum's radius.

$$L_a = 2\pi\cos^{-1} [(R - d)/R]/360 \quad (\text{Equation 3.5})$$

$$CA = L_a \times W \quad (\text{Equation 3.6})$$

where, L_a is the contact length or arc length of the drum in contact with coal (m), CA is the cutting area (m^2), W is the width of cutting drum (m^2), R is the radius of cutting drum (m), d is the depth of cut (m).

3.4.5 Cutting speed

The cutting speed of SM was not uniform across the complete working length of coal face because of intrinsic distinction in coal seam characteristics. Therefore, the average cutting speed of SM was measured by adopting the following measures:

- Working length of coal face was marked at every 10 m as shown in Figure 3.25.
- The front part of undercarriage unit of SM was taken as the starting point.
- Time taken to cut coal for every 20 m in one pass was recorded by a stopwatch.

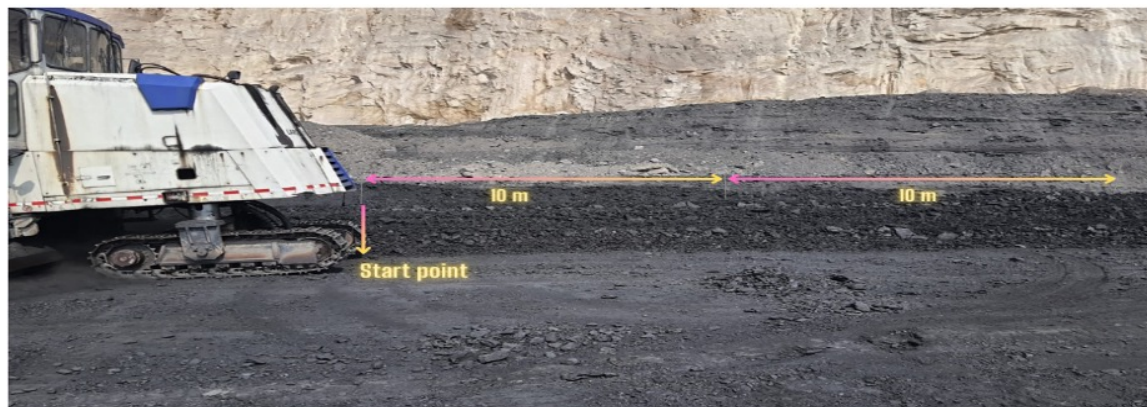


Figure 3.25: Measurement of SM cutting speed at BOCM

3.4.6 Drum speed

The rotational speed of a cutting drum can be controlled by the operator of SM. It relies on the rated power of the machine. The V-belt drive is used to transmit power from the engine shaft to the cutting drum. Drum speed or engine speed was measured by the engine hour meter, whose display monitor was mounted in the operator's cabin of the machine, as shown in Figure 3.26.

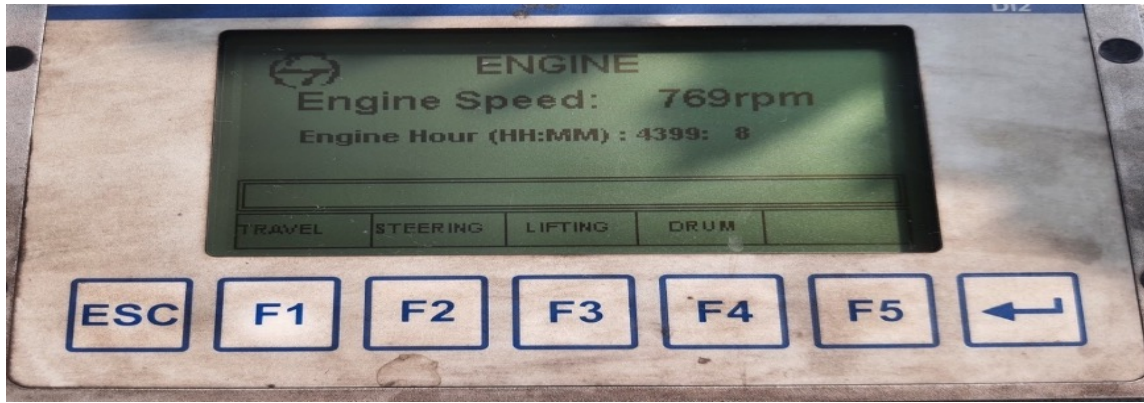


Figure 3.26: Measurement of SM cutting drum’s rotational speed at BOCM

3.5 Field investigations for operational parameter

The measurement of operational parameter is necessary for investigating the SM key productivity indicators in opencast coal mines. Investigations were done to measure face length and machine utilisation, as per methods described as follows:

3.5.1 Face length

Face length on a coal bench was measured as a center-to-center distance between adjacent cuts of coal benches in the direction of SM cutting using measuring tapes.

3.5.2 Machine utilisation

Machine utilisation of SM is used to measure the extent to which the productive capacity of SM is used during its total available time. It was measured as the ratio of machine shift time to scheduled shift time of SM for coal cutting in an opencast mine, as described in Equation 3.7. Machine shift time denotes the actual cutting time of SM in its scheduled shift time.

$$U = (MST \times 100) / (SST) \quad \text{(Equation 3.7)}$$

where, U is the utilisation of surface miner (%), MST is the machine shift time (hour), SST is the scheduled shift time (hour).

3.5.3 Machine shift time

Machine shift time (MST), gauged in hours, was calculated as the difference between initial and final readings of an engine hour meter (EHMR), taken at the shift's start and end in a 24-hour scheduled shift of SM, respectively. EHMR is used to log the actual working time of SM's engine to measure the total cutting time of SM in its scheduled shift.

The hour meter in the SM gets activated by the engine's spark and displays its initial reading in the operator's cabin. It gets triggered by approximately 1.7-m shielded and externally wrapped lead around the engine's spark plug wire. The other wire must be connected to the engine's frame, as shown in Figure 3.27. It begins counting when the engine's speed exceeds idle rpm and records machine shift time, with a maximum value of 9999.9 hours, least count of 0.1 and an accuracy of $\pm 0.02\%$ over the entire range. It operates on a default setting of one spark per revolution with a sampling time of one second. Upon engine shutdown, its display shows an hour icon with the reading of elapsed time, as illustrated in Figure 3.28.

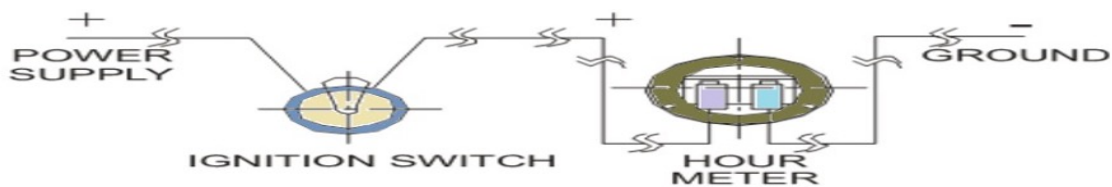


Figure 3.27: Schematic circuit diagram for engine hour meter in the DC series



Figure 3.28: Photograph of Engine hour meter readings for SM

3.6 Field investigations for key productivity indicators of surface miner

3.6.1 Machine productivity

Machine productivity was measured by normalising the gross weight of coal produced with respect to the machine shift time achieved in a 24-hour scheduled shift time of SM during coal cutting, as shown in Equation 3.8. Coal tonnage produced by an excavator is determined either by load weighing or surveyed volume divided by load count (Caterpillar, 2008). In this study, total coal tonnage produced by SM was gauged by multiplying total number of dumpers, total number of trips from each dumper and total weight of the fragmented coal transported in each dumper trip allocated to the SM using an electronic weighbridge, as shown in Figure 3.29. A coal mining electronic belt conveyor weighing scale was also used to verify the total weight of the fragmented coal produced by SM from a specific working coal patch.

$$A_m = \frac{Q}{MST} \quad (\text{Equation 3.8})$$

where, A_m is the machine productivity of SM in an opencast coal mine (t/h), Q is the coal tonnage produced (t), MST is the machine shift time (h).



Figure 3.29: Schematic view of coal production using SM in an opencast coal mine

3.6.2 Pick and diesel consumptions

Pick and diesel consumptions were observed as byproducts of the SM-based coal mining. These consumptions were measured by normalising pick and diesel losses with respect to 1000 tonnes of coal tonnage produced by SM during coal cutting, as given in Equations 3.9 and 3.10, respectively.

$$PC = \frac{PL}{1000 \times Q} \quad (\text{Equation 3.9})$$

$$DC = \frac{DL}{1000 \times Q} \quad (\text{Equation 3.10})$$

where, PC is the pick consumption (n/1000t), PL is the pick loss of SM during coal cutting (n), DC is the diesel consumption (l/1000t), DL is the diesel loss of SM during coal cutting (l), Q is the coal tonnage produced (t).

Pick and diesel losses are inevitable in case of SM-based coal mining during. The total number of picks replaced due to breakage, wear and tear, or detachment from holders in a 24-hour scheduled shift of SM was observed to assess pick loss. Pick breakage typically occurs when the cutting force surpasses the pick's strength. Wear and tear of picks depends on the inorganic hard minerals present in the coal, like quartz and pyrite. Meanwhile, the thermal expansion of the attachment ring causes the detachment of picks for SM during coal cutting. The total number of lost picks in a scheduled shift of SM was carefully counted and recorded in a field record book. Likewise, the total amount of diesel refilled in a 24-hour scheduled shift of SM was observed and recorded in a field record book to assess diesel loss. It was measured by subtracting final readings to the initial reading of the digital meter installed in the SM operator's cabin.

3.6.3 Machine shift cost

Machine shift capital (MSK), gauged as a 'capital' input in lac₹, was measured as a volume of coal produced per unit of owning and operating (O&O) costs in a 24-hour scheduled

shift time. The total O&O costs of SM was calculated using modified ‘Corps of Engineers’ method. The total annual ownership cost of SM was calculated by multiplying the cumulative insurance, tax and interest rates to average annual investment (AAI). Then the hourly cost of ownership was calculated by dividing the annual ownership cost to the number of operating hours of SM in the same year.

However, the operating cost is incurred only when the SM is operated. It depends on various factors, namely, number of operating hours, SM condition and operating conditions at job site. The operating cost was calculated by summing up routine maintenance cost, major breakdown maintenance cost, fuel cost, filter, lubricating oil, and grease costs, manpower cost, pick and holder costs and administrative overhead cost. Then the operating cost per unit of coal volume produced was calculated by dividing the hourly operating cost to the machine productivity. The general guidelines of O&O costs estimation are described as follows:

a) Initial capital cost

Initial capital cost of SM was determined by the machine’s brochure designed by manufacturer to evaluate O&O costs of SM. The initial capital cost of SM is ranged from 300 lac₹ to 650 lac₹ as an expense covered to purchase and prepare the machine for cutting operations in an opencast coal mine.

b) Depreciation cost

The depreciation cost of SM over its useful life was evaluated as a difference between initial cost and the estimated salvage value of machine using straight-line depreciation method. The salvage value for SM was ranged between 60 lac₹ and 130 lac₹. However, the useful life of SM was varied from 6.8 years to 18.5 years depending on the utilisation rate of machine in an opencast mine. Lastly, the depreciation cost of SM was estimated from 685.71 ₹/h to 1485.71 ₹/h.

c) Interest, taxes and insurance costs

The interest cost on initial capital cost can be exactly calculated by considering time value of money and using compound interest rate. However, the annual interest cost was estimated approximately as a product of annual interest rate and average annual investment. Taxes and insurance costs were also calculated as a percentage of the average annual investment. In this study, the cumulative insurance, tax and interest costs were estimated with a rate of 12.5% on average annual investment (cost) over the useful life of SM.

d) Average annual investment

The average annual investment (AAI) for SM was calculated by finding out its average value over the useful life of SM. It was varied between 190.345 lac₹ and 426.11 lac₹.

e) Repair and maintenance costs

Total repair and maintenance costs related to SM were categorised into two categories, which are discussed as follows:

i) Routine maintenance cost

Routine maintenance encompasses wear and tear assessment of the cutting drum and servicing and cleaning of the machine, as presented in Figure 3.30. The annual routine maintenance cost was calculated as 20% of the annual depreciation cost of SM according to machine manuals and trials conducted in coal mines. The repair and maintenance cost of SM for per unit of coal production was calculated by dividing the annual cost by the annual coal production. It was varied between 0.24 ₹/t and 2.68 ₹/t.

ii) Major breakdown maintenance cost

Major breakdowns related to SM like engine overhauls, guide coloumn failure, scraper door breakage, undercarriage unit replacement, hydraulic and fuel tank clean-outs and break hose puncture were considered as major breakdown of SM in opencast coal mines,

as shown in Figure 3.31. The major breakdown maintenance cost was determined to be 2% of annual initial capital cost. It was ranged from 0.23 ₹/t to 4.83 ₹/t.

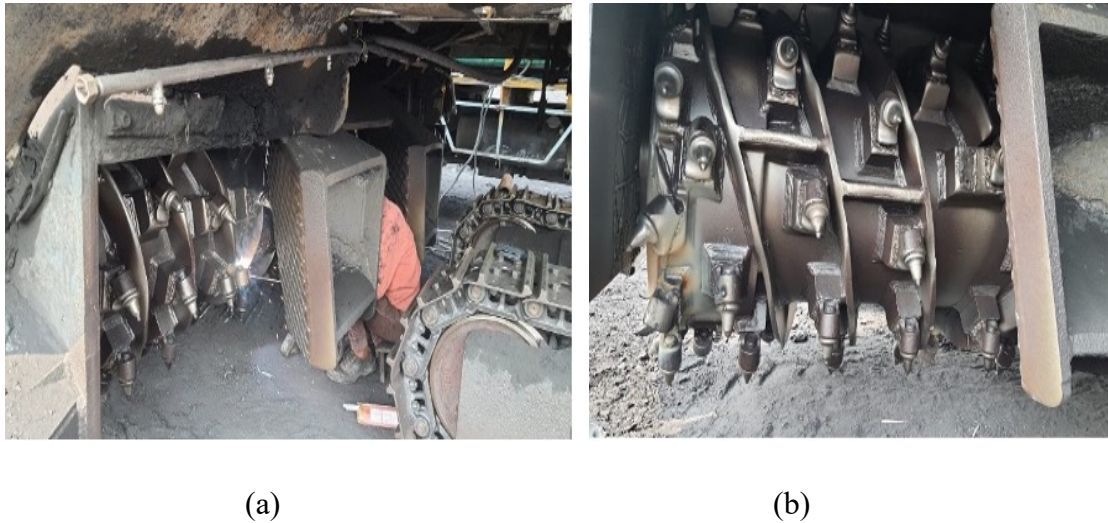


Figure 3.30: Photographs of routine maintenance for SM during coal production: **a)** reinstallation of picks; **b)** cutting drum after reinstalling picks and holders

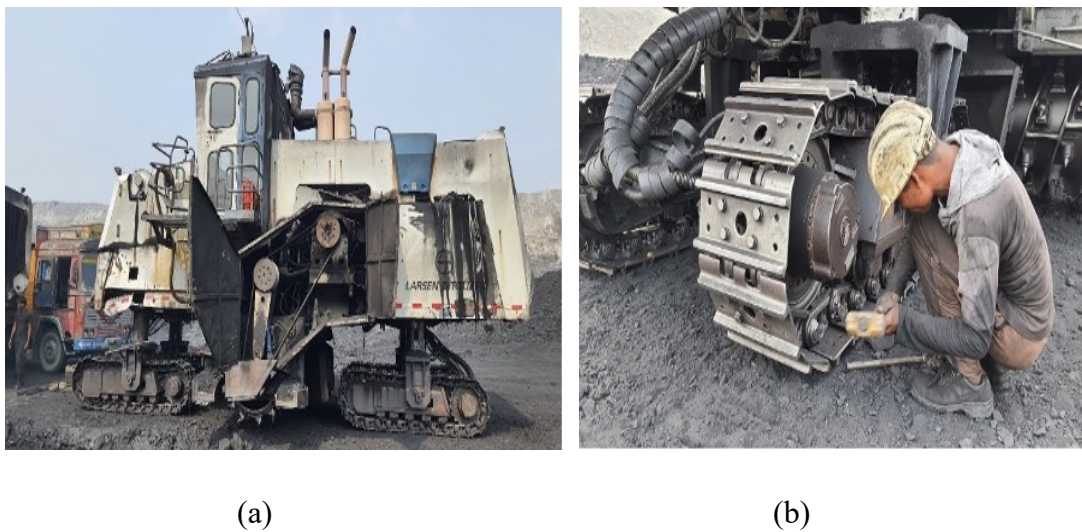


Figure 3.31: Photographs showing major breakdown in SM during coal production: **a)** SM in breakdown state; **b)** reinstallation of undercarriage unit

f) Fuel cost

SM uses diesel as the fuel for its internal combustion engine. The diesel cost of SM was determined by multiplying its unit price to the amount of diesel lost per 1000 tonnes of coal produced in its 24-hour of scheduled shift time. It was varied between 7.25 ₹/t and 20.6 ₹/t.

g) Expense of filter, lubricating oil, and grease

Filter, lubricating oil, and grease (FOG) is needed for the proper functioning of SM. The quantity of FOG required depends on operating hours, frequency of changes, and engine characteristics. FOG costs were determined to be 30% of the hourly diesel costs.

h) Manpower cost

Three pair consisting of an operator and helper is required for operating SM in a 24-hour scheduled shift time. Manpower cost was calculated based on CIL norms, which covers wage, overtime, insurance, bonus, and benefit such as another 28% for paid sick leave. It was ranged between 0.465 ₹/t and 4 ₹/t.

i) Pick and holder costs

Picks and holders were observed as high-wear items with much shorter lifespans than the useful life of SM, as illustrated in Figure 3.32. Pick replacement cost was estimated based on manual guidelines. Pick cost per tonne was determined by multiplying its unit price by the number of picks lost per 1000 tonnes of coal production. It was varied between 0.62 ₹/t and 1.68 ₹/t. Meanwhile, holder cost per tonne was assessed to be 8% of the hourly pick cost based on the past records. It was ranged from 0.23 ₹/t to 0.61 ₹/t.

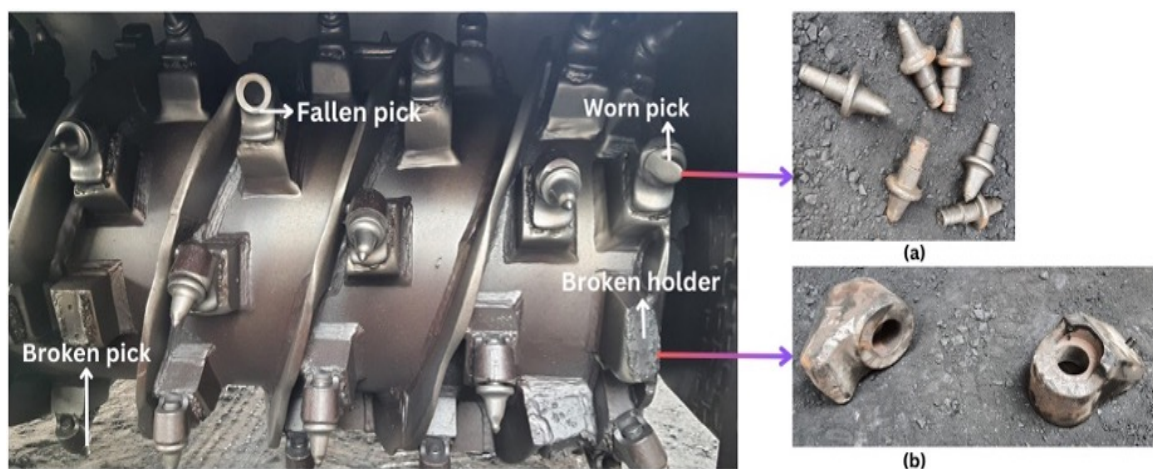


Figure 3.32: High wear items of SM cutting drum for coal production: **a)** pick loss; **b)** holder loss

j) Administrative overhead cost

The administrative overhead cost related to SM was determined to be 2.5% of its annual initial capital cost for mobilisation, assembly and demobilisation of the machine. These cost estimates should be adjusted according to prior experience and managerial discretion. It was varied between 0.29 ₹/t and 6.04 ₹/t.

3.7 Summary of Investigations

A dataset was developed having a total of 47 field-scale SM coal production trials on monthly basis spanning from 2016 to 2021, as detailed in Table 3.23. Detailed calculations pertaining to the MSK for various SM-based coal production trials are provided in Appendix C. Table 3.24 details the coal parameter investigated at various opencast mines and determined in the laboratory. The corresponding machine and operational parameters against key productivity indicators of SM are summarised in Tables 3.25 and 3.26. All the field measurement data related to them are provided in Appendix B.

Legends used in Tables 3.23, 3.24, 3.25, and 3.26 are explained as follows:

UCS is the uniaxial compressive strength (MPa), TS is the tensile strength (MPa), AC is the ash content (%), MC is the moisture content (%), W is the width of cutting drum (m), P_{CD} is the rated power for cutting drum (kW), D is the cutting depth (m), CA is the cutting area (m^2), V is the cutting speed (m/min), FL is the length of face (m), U is the utilisation of machine (%), A_M is the machine productivity of SM in an opencast coal mine (t/h), PC is the number of picks consumed per 1000 tonnes of coal production (n/1000t), DC is the diesel consumption per 1000 tonne of coal production (l/1000t), Q is the monthly coal production by SM (t), MST is the machine shift time of SM on monthly basis (h), PL is the pick loss during coal production on monthly basis (n), DL is the diesel loss during coal production on monthly basis (l), O&O is the ownership and operating costs of SM (₹/t), MSK is the machine shift cost of SM on monthly basis (lac ₹).

Table 3.23: Summary of parametric investigations for monthly coal production by SM

S. N.	Opencast coal mine	Location	SM code	Q (t)	MST (h)	A _M (t/h)	PL (n)	DL (l)	O&O (₹/t)	MSK (lac ₹)
1	Nigahi (NOCM)	P1-a	C	171892.5	279.5	615	112	18564.4	21.09	36.25
2		P1-b		39600	180	220	38	7326	59.65	23.62
3		P1-c		36115.2	158.4	228	36	7764.8	66.15	23.89
4		P2-a		134531.64	225.8	595.8	83	12565.3	19.82	26.66
5		P2-b		34916.4	190.8	183	25	5876.4	62.59	21.85
6	Jayant (JOCM)	T3-a	C	249541.48	357.1	698.8	120	25453.2	18.36	45.82
7		T3-b		174278.8	364.6	478	85	17776.4	21.97	38.29
8		T3-c		68027	230.6	295	68	10544.2	42.17	28.69
9	Bhubaneswari (BOCM)	B _m 2-a	E	239346.28	357.1	670.2	132	20344.4	19.18	45.91
10		B _m 3-b		185068.8	288	642.6	109	17581.5	21.79	40.33
11		B _m 4-c		305575.2	302.4	1010	NA	NA	NA	NA
12		B _m 4-d		161179.2	302.4	533	105	17729.7	26.31	42.41
13		B _m 5-a		317116.8	316.8	1001	NA	NA	NA	NA
14		B _m 5-b		162500	312.5	520	98	22262.5	30.53	49.61
15		B _m 5-c		41580	252	165	42	8149.7	84.89	35.3
16	Rajmahal (ROCM)	R _m 3-a	E	232560	342	715	93	22093.2	20.08	46.7
17		R _m 3-b		40614	193.4	949	30	6904.4	67.91	27.58
18		R _m 2-a		271656	352.8	245	120	23090.8	17.57	47.73
19		R _m 2-b		72468	237.6	455	45	10145.5	44.25	32.07
20	Parsa East & Kanta Basan (PEKB)	H _m 4-a	E	244673	342.2	343	115	22020.6	19.28	47.17
21		H _m 4-b		368971.2	388.8	111	144	27672.8	14.59	53.83
22		H _m 4-c		58212	237.6	145	37	7276.5	48.83	28.42
23		H _m 5-a		152334	334.8	784	76	19041.8	30.50	46.46
24		H _m 5-b		103723.2	302.4	920	83	14521.2	40.12	41.61
25		H _m 5-c		22377.6	201.6	220	20	4251.7	119.83	26.82
26		H _m 5-d		30203.5	208.3	680	32	5587.6	94.72	28.61
27		H _m 6-a		316108.8	403.2	210	136	24656.5	16.39	51.81
28		H _m 6-b		349048	379.4	770	140	26876.7	15.12	52.78
29		H _m 6-c		47520	216	305	40	7128	60.34	28.67
30	Samleswari (SOCM)	L1-a	A	180682.3	386.9	467	108	21139.8	23.88	43.15
31		L1-b		64800	288	225	55	13089.6	56.89	36.86
32		L1-c		48384	252	192	46	10450.9	67.45	32.64
33	Lakhanpur (LOCM)	L2-a	A	215119.8	379.4	567	110	23232.9	20.32	43.71
34		L2-b		85449.6	331.2	258	64	12646.5	40.36	34.49
35	Gevra (GOCM)	UK1-a	D	123161.5	319.9	385	64	13547.8	30.67	37.77
36		UK1-b	B	122709.6	280.8	437	77	12025.5	24.40	29.94
37		UK1-c		121586.4	280.8	433	71	12401.8	25.09	30.51
38		UK1-d	D	41832	252	166	40	6065.6	69.25	28.97
39		LK2-a		183768	372	494	72	16539.1	22.57	41.48
40		LK2-b	E	231927.5	319.9	725	93	17858.4	17.24	39.98
41		LK2-c	D	33805.35	245.5	137.7	31	5408.9	85.17	28.79
42		UK3-a		262008	432	606.5	121	23056.7	19.58	51.3
43		UK3-b	E	209664	327.6	640	113	18031.1	19.91	41.74
44		UK3-c	D	34914	253	138	33	6703.5	94.23	32.9
45		LK4-a	B	99792	259.2	385	63	14270.3	34.25	34.18
46	LK4-b	D	130046.4	316.8	410.5	74	12744.5	27.65	35.96	
47	LK4-c	E	35358.4	200.9	176	31	6081.6	77.73	27.48	

Table 3.24: Summary of laboratory investigations

Mine particular			Coal parameter					
Opencast mine, Coalfield name	Seam name	Sample name	Coal type	UCS (MPa)	TS (MPa)	AC (%)	MC (%)	
Nigahi (NOCM), Singrauli coalfield, NCL	Purewa top	P1-a	Coal	18.8	2.2	30.5	6.8	
		P1-b	Shaly coal	30.75	3.3	44.8	7	
		P1-c	Carbonaceous shale	29.48	3.47	46.7	10.1	
	Purewa bottom	P2-a	Coal	16.4	1.6	26.3	9.1	
		P2-b	Shaly coal	31.13	2.52	41.5	7.4	
Jayant (JOCM), Singrauli coalfield, NCL	Turra	T3-a	Coal	24.7	2	31.3	7.5	
		T3-b	Coal	22.5	2.1	30	5.4	
		T3-c	Carbonaceous shale	25.6	3.5	50.5	6.8	
Bhubaneswari (BOCM), Talcher coalfield, MCL	II	B _m 2-a	Coal	14.45	1.35	28.8	6.1	
	III	B _m 3-b	Coal	27.8	0.9	29.7	5.1	
	IV	B _m 4-c	Coal	12.6	1.2	34.9	4.3	
	IV	B _m 4-d	Shaly coal	16.45	2	40.1	4.2	
	V	B _m 5-a	Coal	22.1	1.8	34.6	4.1	
		B _m 5-b	Shaly coal	26.52	2.5	37.3	6.8	
B _m 5-c		Carbonaceous shale	34.62	3.7	50.6	4.9		
Rajmahal (ROCM), Rajmahal coalfield, ECL	III	R _m 3-a	Coal	15.42	1	30	7.2	
		R _m 3-b	Shaly coal	34.95	2.63	38.7	7.6	
	II	R _m 2-a	Coal	14.92	0.9	29.6	6	
		R _m 2-b	Carbonaceous shale	18.42	2	51.3	7.2	
Parsa East & Kanta Basan (PEKB), Hasdeo Arand coalfield, SECL	IV	H _m 4-a	Coal	10.54	2.1	26.1	1.5	
		H _m 4-b	Coal	9.41	1.75	22.8	3.2	
		H _m 4-c	Shaly coal	18.98	1.78	39.1	5.1	
	V	H _m 5-a	Coal	22.28	1.63	33.9	2.2	
		H _m 5-b	Coal	27.58	3.22	28.4	3.8	
		H _m 5-c	Shaly coal	31.5	3.5	47.1	5.9	
		H _m 5-d	Carbonaceous shale	19.4	2.9	53.7	5.2	
	VI	H _m 6-a	Coal	8.92	1.55	33.1	5.2	
		H _m 6-b	Coal	12.72	0.91	30.2	4.4	
		H _m 6-c	Shaly coal	32.42	2.89	39.1	2.5	
Samaleswari (SOCM), IB Valley, MCL	Lajkura	L1-a	Coal	13.4	1.9	29.7	9	
		L1-b	Shaly coal	31.38	2.4	44.8	8.8	
		L1-c	Carbonaceous shale	25.5	2	52.7	9.6	
Lakhanpur (LOCM), IB Valley, MCL	Lajkura	L2-a	Coal	17.65	1.2	32	6.3	
		L2-b	Shaly coal	27.46	2.2	41.5	11.4	
Gevra (GOCM), Korba coalfield, SECL	Central zone	Upper Kusmunda	UK1-a	Coal	20.05	2.79	24.3	4.8
			UK1-b	Coal	20	3.3	22.4	4.2
			UK1-c	Coal	21.05	3	23.8	6
			UK1-d	Shaly coal	27.6	3.74	42	6.8
		Lower Kusmunda	LK2-a	Coal	18.37	1.35	27.5	5.2
			LK2-b	Coal	11.11	1.75	23	9
			LK2-c	Shaly coal	27.6	3.4	39.3	3.6
	East zone	Upper Kusmunda	UK3-a	Coal	20.2	1.97	32.3	7.8
			UK3-b	Coal	15.05	1.35	29.4	7.2
			UK3-c	Carbonaceous shale	29.4	3.44	56.8	3
		Lower Kusmunda	LK4-a	Coal	19.8	3.08	29.1	5.5
LK4-b			Coal	28.16	2.02	26	6.9	
LK4-c			Shaly coal	35.8	2.73	39.5	8.1	

Table 3.25: Summary of machine and operational parameters with key productivity indicators of SM in opencast coal mines

S. N.	Opencast coal mine	Location	SM model name	SM code	Coal type	Machine parameter						Operational parameter		Key productivity indicators	
						W (m)	P _{CP} (kW)	D (m)	CA (m ²)	V (m/min)	FL (m)	U (%)	A _m (t/h)	PC (n/1000t)	DC (t/1000t)
1	Nigahi (NOCM)	P1-a	KSM403	C	Coal	4	471	0.30	4.29	20	150	37.6	615	0.65	108
		P1-b	KSM403		Shaly coal	4	471	0.18	3.25	15	140	25	220	0.95	185
		P1-c	KSM403		Carbonaceous shale	4	471	0.18	3.25	15	120	22	228	1	215
2		P2-a	KSM403		Coal	4	471	0.30	4.29	22	130	33.6	595.8	0.62	93.4
		P2-b	KSM403		Shaly coal	4	471	0.10	2.39	18	130	26.5	183	0.73	168.3
3	Jayant (JOCM)	T3-a	KSM403	C	Coal	4	471	0.20	3.44	22	190	48	698.8	0.48	102
		T3-b	KSM403		Coal	4	471	0.20	3.44	18	200	49	478	0.49	102
		T3-c	KSM403		Carbonaceous shale	4	471	0.15	2.96	17	150	31	295	1	155
4	Bhubaneswari (BOCM)	B _m 2-a	2200SM3.8	E	Coal	3.8	471	0.25	3.69	22	180	48	670.25	0.55	85
		B _m 3-b	2200SM3.8		Coal	3.8	471	0.25	3.69	20	150	40	642.6	0.59	95
		B _m 4-c	2200SM3.8		Coal	3.8	471	0.35	4.44	18	130	45	1010.5	N/A	N/A
5		B _m 4-d	2200SM3.8		Shaly coal	3.8	471	0.25	3.69	15	150	42	533	0.65	110
		B _m 5-a	2200SM3.8		Coal	3.8	471	0.35	4.44	10	180	44	1001	N/A	N/A
6		B _m 5-b	2200SM3.8		Shaly coal	3.8	471	0.25	3.69	9	150	42	520	0.6	137
		B _m 5-c	2200SM3.8		Carbonaceous shale	3.8	471	0.15	2.81	6	90	35	165	1	196
7	Parsa East & Kantia Basan (PEKB)	H _m 4-a	2200SM3.8	E	Coal	3.8	471	0.30	4.07	24	160	46	715	0.47	90
		H _m 4-b	2200SM3.8		Coal	3.8	471	0.28	3.92	25	175	54	949	0.39	75
		H _m 4-c	2200SM3.8		Shaly coal	3.8	471	0.20	3.27	16	150	33	245	0.63	125
8		H _m 5-a	2200SM3.8		Coal	3.8	471	0.25	3.69	19	120	45	455	0.5	125
		H _m 5-b	2200SM3.8		Coal	3.8	471	0.25	3.69	10	120	42	343	0.8	140
9		H _m 5-c	2200SM3.8		Shaly coal	3.8	471	0.13	2.61	12	80	28	111	0.88	190
		H _m 5-d	2200SM3.8		Carbonaceous shale	3.8	471	0.20	3.27	10	100	31	145	1.05	185
10		H _m 6-a	2200SM3.8		Coal	3.8	471	0.30	4.07	26	160	56	784	0.43	78
		H _m 6-b	2200SM3.8		Coal	3.8	471	0.28	3.92	25	160	51	920	0.4	77
11		H _m 6-c	2200SM3.8		Shaly coal	3.8	471	0.20	3.27	16	140	30	220	0.85	150

Table 3.26: Summary of machine and operational parameters with key productivity indicators of SM in opencast coal mines

S. N.	Opencast mine	coal	Location	SM model name	SM code	Coal type	Machine parameter						Operational parameter		Key productivity indicators		
							W (m)	P _{GD} (kW)	D (m)	C _A (m ²)	V (m/min)	FL (m)	U (%)	A _m (t/h)	P _C (m/1000t)	DC (t/1000t)	
26	Rajnahal (ROCM)		R _m 3-a	2200SM3.8	E	Coal	3.8	471	0.30	4.07	20	140	47.5	680	0.4	95	
27			R _m 3-b	2200SM3.8		Shaly coal	3.8	471	0.15	2.81	12	110	26	210	0.75	170	
28			R _m 2-a	2200SM3.8		Coal	3.8	471	0.30	4.07	19	150	49	770	0.44	85	
29	Samleswari (SOCM)		R _m 2-b	2200SM3.8		Carbonaceous shale	3.8	471	0.25	3.69	14	140	33	305	0.62	140	
30			L1-a	KSM 303	A	Coal	3	397	0.28	3.10	21	120	52	467	0.6	117	
31			L1-b	KSM 303		Shaly coal	3	397	0.15	2.22	18	100	40	225	0.85	202	
32			L1-c	KSM 303		Carbonaceous shale	3	397	0.15	2.22	14	100	35	192	0.95	216	
33	Lakhanpur (LOCM)		L2-a	KSM 303	A	Coal	3	397	0.21	2.65	22	150	51	567	0.51	108	
34			L2-b	KSM 303		Shaly coal	3	397	0.15	2.22	15	130	46	258	0.75	148	
35	Gevra (GOCM)	Central zone	UK1-a	2200 SM	D	Coal	2.2	471	0.20	1.89	20	120	43	385	0.52	110	
36			UK1-b	KSM 304	B	Coal	3	595	0.25	2.91	17	150	39	437	0.63	98	
37			UK1-c	KSM 304		Coal	3	595	0.25	2.91	18	160	39	433	0.58	102	
38			UK1-d	2200 SM	D	Shaly coal	2.2	471	0.15	1.63	15	100	35	166	0.95	145	
39			LK2-a	2200 SM		Coal	2.2	471	0.20	1.89	22	135	50	494	0.39	90	
40			LK2-b	2200SM3.8	E	Coal	3.8	471	0.28	3.92	25	150	43	725	0.4	77	
41			LK2-c	2200 SM	D	Shaly coal	2.2	471	0.15	1.63	15	80	33	137.7	0.92	160	
42	East zone		UK3-a	2200 SM		Coal	2.2	471	0.18	1.79	25	150	60	606.5	0.46	88	
43			UK3-b	2200SM3.8	E	Coal	3.8	471	0.25	3.69	22	140	45.5	640	0.54	86	
44			UK3-c	2200 SM	D	Carbonaceous shale	2.2	471	0.16	1.68	12	120	34	138	0.94	192	
45			LK4-a	KSM 304	B	Coal	3	595	0.28	3.10	14	120	36	385	0.63	143	
46			LK4-b	2200 SM	D	Coal	2.2	471	0.18	1.79	24	140	44	410.5	0.57	98	
47			LK4-c	2200SM3.8	E	Shaly coal	3.8	471	0.15	2.81	12	110	27	176	0.88	172	

3.8 Observations

Coal, machine, and operational parameters were analysed in various Indian opencast coal mines to get a better understanding of their influence on the key productivity indicators of SM in opencast coal mines. The count, mean, minimum and maximum range of variation with standard deviation and standard error of each factor related to all parameters, key productivity indicators and total factor productivity of SM are detailed in Table 3.27.

Table 3.27: Descriptive statistics of parameters affecting key productivity indicators

Particular	Factors	Count	Min.	Max.	Range	Mean	Stand. error	Stand. dev.
Coal parameter	UCS	47	8.92	35.8	26.88	22.15	1.08	7.37
	TS	47	0.9	3.74	2.84	2.27	0.12	0.84
	AC	47	22.4	56.8	34.4	35.68	1.35	9.25
	MC	47	1.5	11.4	9.9	6.1	0.31	2.16
Machine parameter	W	47	2.2	4	1.8	3.4	0.1	0.7
	P _{CD}	47	397	595	198	471	5.8	40
	D	47	0.1	0.35	0.25	0.22	0.009	0.06
	CA	47	1.63	4.44	2.81	3.15	0.12	0.83
	V	47	6	26	20	17.57	0.72	4.93
Operational parameter	FL	47	80	200	120	136.2	3.97	27.21
	U	47	22	60	38	39.8	1.33	9.166
Key productivity indicators	A _M	47	111	1010.5	899.5	457.9	36.96	253.4
	PC	47	0.39	1.05	0.66	0.667	0.03	0.204
	DC	47	75	216	141	130	6.37	42.76
Total factor productivity	Q	47	22377.6	368971.2	346593.6	138535	14120.2	94721.2
	PL	47	20	144	124	76	5	36
	DL	47	4251.7	27672.8	23421.1	14633.3	1015.3	6811
	MST	47	158.4	432	273.6	434.2	34.4	230.8
	MSK	47	21.85	53.83	31.98	37.13	1.3	8.8

It is important to know the range in which the maximum frequency or count of coal parameter falls because this will help in projecting and guiding the range in which machine is likely to perform. Range and count of coal parameter are given in Table 3.28. The

compressive strength of coal varied between 8.92 MPa and 35.8 MPa, maximum in the range of 15 MPa to 20 MPa. The average tensile strength was around one-tenth of average uniaxial compressive strength. Tensile strength, ash content and moisture content dominantly ranged in between 1.5 MPa to 2 MPa, 25% to 30%, and 6% to 7.5%, respectively.

Table 3.28: Range and count of coal parameter in opencast coal mines

Uniaxial compressive strength (MPa)		Tensile strength (MPa)		Ash content (%)		Moisture content (%)	
Range	Count	Range	Count	Range	Count	Range	Count
05-10	2	0.5-1.0	4	20-25	5	1.5-3.0	4
10-15	7	1.0-1.5	5	25-30	13	3.0-4.5	8
15-20	12	1.5-2.0	13	30-35	9	4.5-6.0	12
20-25	7	2.0-2.5	7	35-40	6	6.0-7.5	13
25-30	11	2.5-3.0	7	40-45	6	7.5-9.0	6
30-35	7	3.0-3.5	9	45-50	2	9.0-10.5	3
35-40	1	3.5-4.0	2	50-58	5	10.5-12	1

Ash and moisture contents of coal were determined with an objective to evaluate their influence especially on pick consumption. The ash content in coal was below 35%, but it was more in shaly coal and carbonaceous shale. Ash content dominantly ranged in between 25% to 30% for coal, 40% to 45% for shaly coal and 50% to 55% for carbonaceous shale, respectively. The less value of ash content in coal was due to the absence of layers of shale or dirt bands, although their presence was very common in opencast coal mines. Moreover, such subtle differences were not found for moisture content in between coal and shaly coal or coal and carbonaceous shale.

3.8.1 Outliers

A dataset with a total of 47 field-scale SM coal production trials was analysed to select outliers using least-squares regression method. Table 3.29 shows the result of bivariate linear regression model for coal production based on machine shift time (MST) to assess the goodness of fit. Pearson correlation coefficient (R) and coefficient of determination (R^2) between coal production and MST were observed as 0.824 and 0.6787, respectively. These values are indicating that the model is a good fit for the data.

Table 3.29: Results of coal production model based on machine shift time

R	R square	Adjusted R square	Standard error of the estimate	Observations
0.824	0.6787	0.672	56566.26	47

ANOVA allows testing the hypothesis that there is no linear relationship between coal production and MST, which was indicated by $R_{0pop} = 0$. ANOVA produced the F-value as 95.1, which is greater than the critical value of F (1,46) as 4.05 at 0.05 significance level with a significance of 1.1×10^{-12} indicating $R_{0pop} = 0$ was rejected for “representative of the population” and relationship between variables was found to be statistically significant in terms of linearity. ANOVA results are given in Table 3.30.

Table 3.30: Results of ANOVA test for bivariate coal production model

Particular	Degree of freedom	Sum of squares	Mean square	F-value	Significance
Regression	1	304214746651.7	304214746651.7	95.1	0.000
Residual	45	143988384813.9	3199741885		
Total	46	448203131465.7			

For a t-test, t stat was observed as 9.75, which is greater than the critical value of t (1,46) as 2.01 at 0.05 significance level with a p-value as 1.1×10^{-12} indicating regression coefficient of MST significantly differ from zero for “representative of the population” and coal production is unlikely not to have a linear relationship with MST. Results of t-test are detailed in Table 3.31. In addition, zero did not appear between lower and upper range coefficient at 0.05 significance level, hence, this model was confirmed as a statistically significant model.

Table 3.31: Regression statistics of machine shift time-based coal production model

Particular	Coefficients	Standard Error	t stat	P-value	Lower 95%	Upper 95%
Intercept	-209765.4	37372	-5.6	0.000	-285036.5	-134494.4
MST	1214.3	124.5	9.75	0.000	963.5	1465.15

Figure 3.33 illustrates a plot between actual and predicted values confirming that the values fall near the straight line for coal production, hence, validating the statistical significance of the developed model at 0.05 significance level.

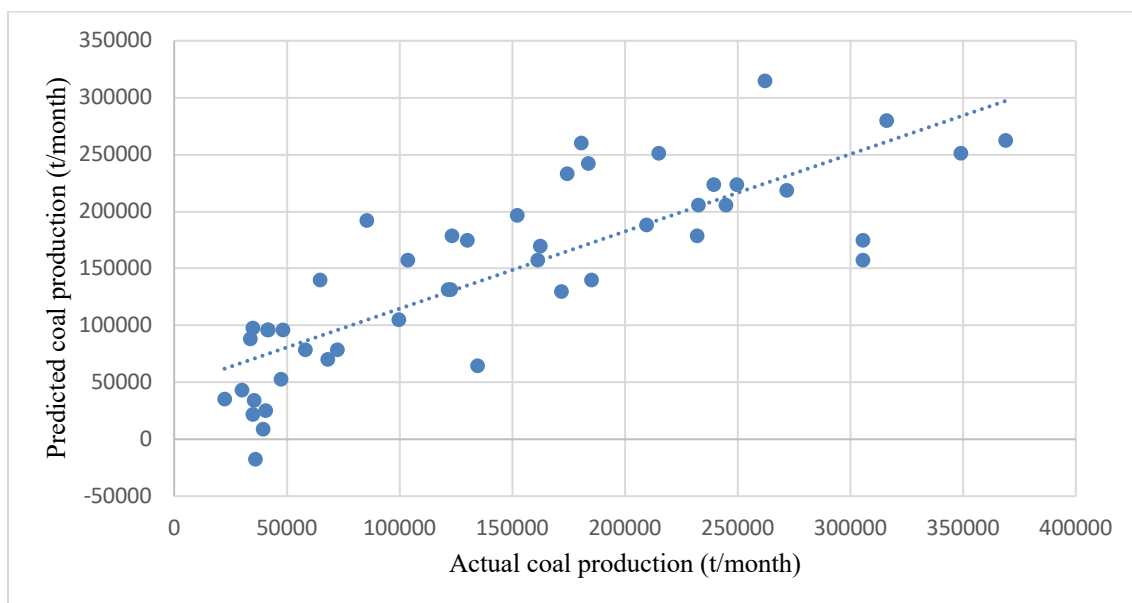


Figure 3.33: Graph between actual and predicted values for bivariate coal production model

Two set of data points from the dataset of 47 field-scale SM coal production trials were identified vis-à-vis eliminated as outliers for having standardised residuals of 2.3 and 2.6 based on linear regression analysis between coal production and MST using the criterion of being more than two standard deviations away from the mean of residuals (Hunasigi *et al.*, 2023). Figure 3.34 shows the result for outliers based on scatter plot between predicted coal production and regression standardised residual of the bivariate coal production model with zero mean and constant variance.

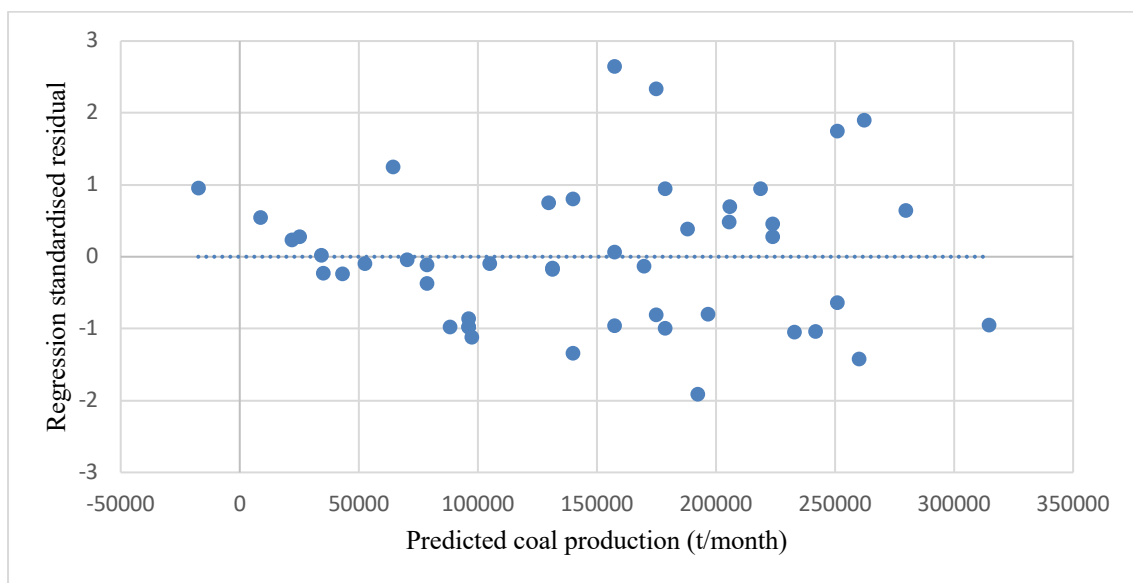


Figure 3.34: Graph between predicted coal production and regression standardised residual

