2 LITERATURE REVIEW

2.1 Introduction

Mechanical cutting is pivotal in contemporary coal mining due to its techno-economic benefits, safety improvements, and streamlined production. Surface miner (SM), a state-of-the-art technology, are increasingly essential for coal mining due to the stringent ground vibration limits for the safety of nearby sensitive structures and residential areas. It produces coal worldwide, including in Australia, Canada, China, India, Indonesia, Russia, South Africa, and USA. Currently, around 150 units of SM are operating in Indian opencast coal mines. Figure 2.1 illustrates a schematic diagram of L&T made KSM 303.

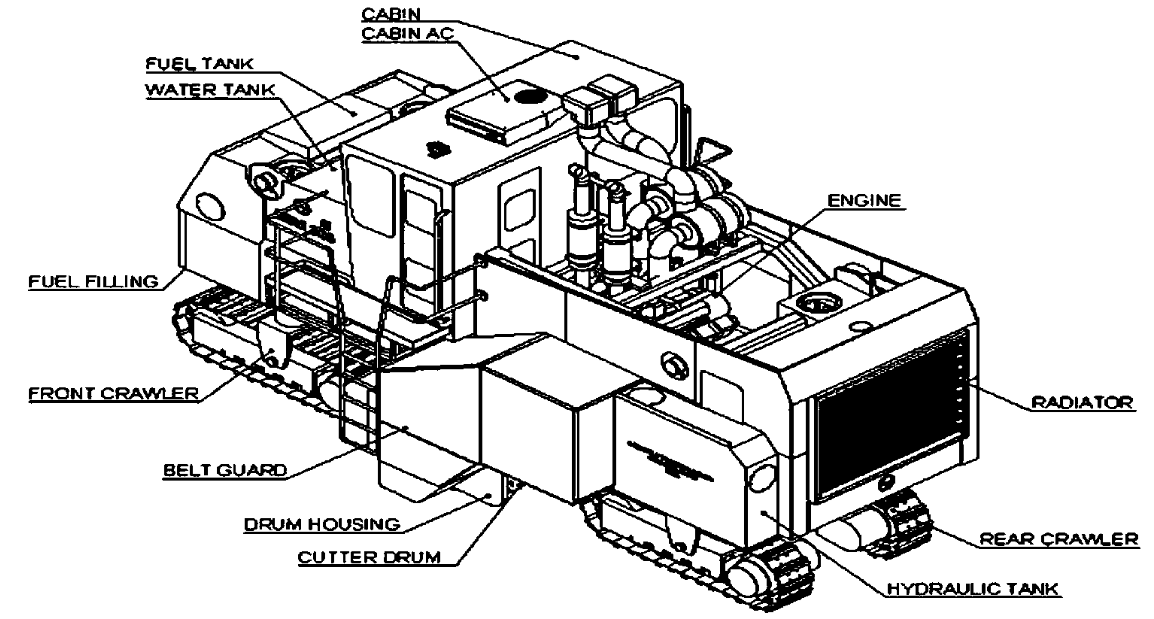


Figure 2.1: Schematic top view of L&T made Surface Miner KSM303

In this study, a comprehensive literature has been summarised related to the type, development, design, construction, cutting mechanism, operating methods and rated production capacity of SM. Theoretical cutting force models based on mechanical coal cutting mechanics and energy productivity models for conical picks developed by various researchers, highlighting their features and limitations have been reviewed in subsequent sections. Machine productivity models also have been reviewed to identify the factors related to coal, machine and operational parameters, influencing key productivity indicators of surface miner in opencast mines along with the production functions measuring total factor productivity developed by various researchers. Lastly, research gap, and novelty of research work are discussed.

2.2 Surface Miner

Surface miner (SM) has demonstrated its applicability in cutting soft to medium-hard rock selectively, limited to a cutting depth of 0.1 m having uniaxial compressive strength (UCS) up to 80 MPa and hardness value up to 6 at Mohs hardness scale (Ghose, 2008; Dey and Bhattacharya, 2012). It can handle flat or gently sloping coal seams with transverse slopes of up to 8^0, depending on local conditions (Wirtgen, 2008). It requires stable, consolidated, plain and levelled ground for operations.

Regardless of the promising benefits and successful applications of SM technology in coal mining worldwide, its universal acceptance remains limited due to rigid boundary conditions, some primarily influenced by natural factors often beyond human control. For example, the absence of discontinuities and high in-situ stress levels can significantly elevate cutting resistance. Major geological features such as faults, shears, folds, and igneous intrusions may locally alter the in-situ stress conditions.

2.2.1 Types

SM can be categorised into three distinct groups depending on the type and placement of its cutting housing, as described as follows. Table 2.1 presents the technical specifications of selected prominent models of SM.

(a) SM with a front cutting wheel featuring a multi-bucket cutting drum positioned in front of the machine like Krupp.

(b) SM with a boom-type cutting drum positioned at front of the machine fitted with point-attack cutting tools, such as Takraf, Tesmec, and Vermeer.

(c) SM with a conical picks-attached cutting drum positioned in the middle of the machine between front and rear crawler tracks, near the centre of gravity, such as Wirtgen, Bitelli, L&T.

In India, Wirtgen's SM model 1900 SM, debuted in 1994 for trial operations at the limestone mine of Gujrat Ambuja Cement Limited, addressing restricted blasting conditions (Dey and Bhattacharya, 2012). A significant advancement occurred on June 21, 1999, with the deployment of the Wirtgen 2100 SM at the Lakhanpur opencast coal mine, Mahanadi Coalfields Limited (MCL), marking a breakthrough in coal mining (Prakash *et al.*, 2013). Figure 2.2 illustrates the annual applicability of SM in terms of its share percentage in MCL's total coal production. Table 2.2 details the coal production by SM for CIL in FY 2019-20 and FY 2020-21.

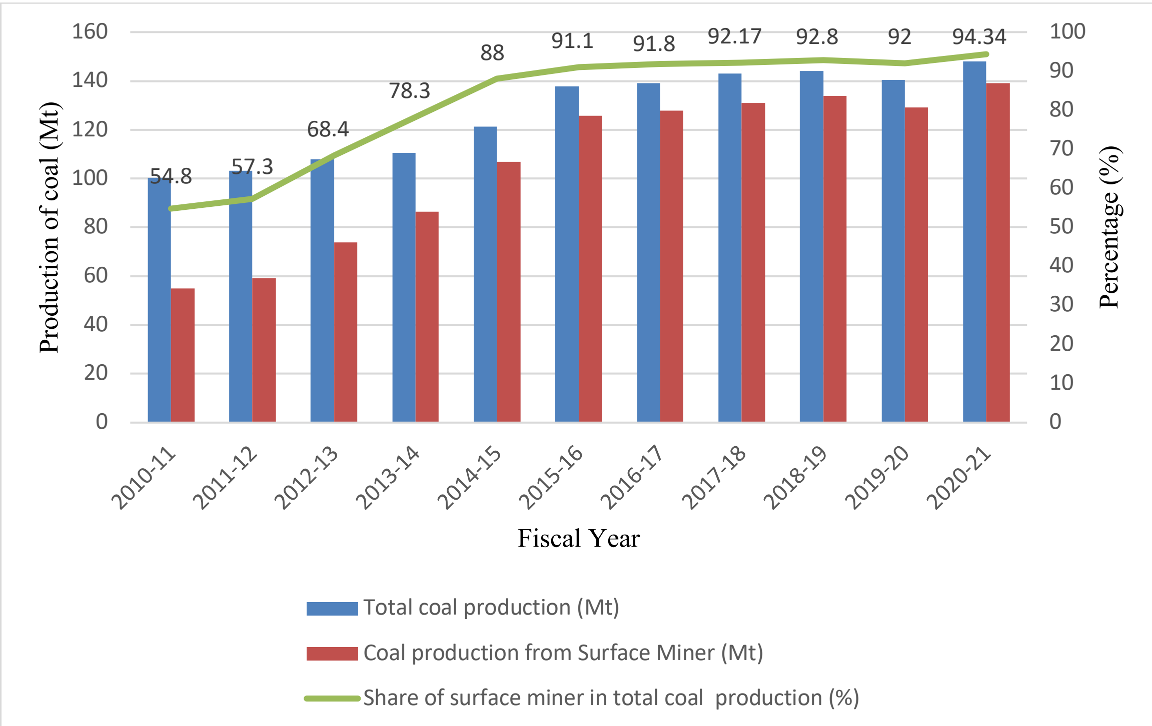


Figure 2.2: Annual applicability trend of SM in Mahanadi Coalfields Limited

Table 2.1: Comparison of basic technical specifications across different SM models

Brand	Model Name	Drum diameter with tools (m)	Rated engine power (kW)	Drum width (m)	Max. cutting depth (m)	Cutting speed (m/min)	RPM at max. torque	Dimension as L×W×H (m^3)
L&T	KSM 223	1.15	597	2.2	0.3	0-30	1900	8.8×3.4×4.35
	KSM 303	1.15	597	3	0.4	0-30	1900	8.5×4.1×4.5
	KSM 304	1.35	895	3	0.35	0-20	1900	10.8×4.6×5.5
	KSM 403	1.15	708	4	0.3	0-25	1800	8.5×4.6×4.5
Wirtgen	2200 SM	1.12	708	2.2	0.25	0-84	2100	9.7×3.3×3
	2200 SM 3.8	1.3	708	3.8	0.35	0-84	2100	9.3×3.8×3
	2500 SM	1.5	783	2.5	0.65	0-25	N/A	22.7×3.47×4.9
	4200 SM	1.5	1,119	4.2	0.65	0-20	N/A	28.2×5.43×6.5
Bitelli	SF 150	N/A	370	1.5	0.34	0-30	2100	14.48×1.5×4
	SF 200 L	N/A	370	2	0.3	0-30	2100	14.48×2×4
	SF 200 LE	N/A	420	2.01	0.32	0-36	1800	7.35×2.01×4
Takraf	MTS 180	1.4	500	3.2	0.6	0-20	N/A	N/A
	MTS 250	1.6	740	3.5	0.8	0-20	N/A	N/A
	TSM 300	1.6	839	3.8	0.8	0-20	N/A	N/A
Tesmec	975EVO	N/A	280	2.86	0.35	0-300	2000	8.22×2.86×3.2
	1150EVO	N/A	328	3.2	0.50	0-241	2100	10.45×3.2×3.5
	1475EVO	1.88	470	4.2	0.50	0-181	2000	12×4.2×3.78
Vermeer	T1055	N/A	310	3.4	0.813	0-34.7	2100	9.8×2.9×3.4
	T1155	N/A	403	3.4	0.635	0-44.2	2100	11.4×3×3.7
	T1255	N/A	447	3.7	0.686	0-36	2100	8.89×3.4×3.71
	T1655	N/A	895	4.5	0.71	0-39	1800	12.7×6.2×5.1
Trencor	T1460	N/A	470	3.84	1.067	0-134	2100	12×3.84×4.2
	T1660	N/A	597	3.9	N/A	0-127	2100	14.3×3.9×4.3
	T1760	N/A	708	4.5	1.067	0-240	2100	13.16×4.5×4.4
Krupp	KSM 2000	3.55	1,000	5.6	2.25	0-111.6	N/A	17.7×5.6×9.5
	KSM 4000	3.66	2,309	7.11	2.75	0-115	N/A	22.9×7.1×11.6

Table 2.2: Mine-wise coal production by SM in opencast coal mines of CIL

S. No.	Name of mine	Coal production by surface miner (Mt)			
		2019-20		2020-21	
		Departmental	Outsourcing	Departmental	Outsourcing
1.	Basundhara w.	1.77		0.81	
2.	Garjanbahal	5.33	2.12	8.67	3.10
3.	Lajkura		2.61	0.55	3.82
4.	Samaleswari	3.22	1.17	2.15	
5.	Belpahar	0.49	6.68	0.55	6.63
6.	Lakhanpur	2.09	18.38	2.89	18.10
7.	Hingula	4.56	2.02	4.73	1.62
8.	Balram	5.05		4.88	0.82
9.	Ananta	1.92	7.73	1.6	6.25
10.	Bhubaneswari		28		28
11.	Jagannath	0.03	0.09		3.61
12.	Bharatpur		2.69		5.4
13.	Lingraj	6.67	5.87	6.18	5.44
14.	Kaniha		7.53		7.94
15.	Kulda	0.74	12.36	1.21	14.17
	Total MCL	**31.85**	**97.24**	**34.23**	**104.91**
1.	Dudhichua	2.46		2.7	
2.	Jayant	4.05		3.63	
3.	Krishnshila	2.3		2.40	
4.	Nigahi			0.87	
	Total NCL	**8.80**		**9.60**	
1.	Gevra		37.55		30.34
2.	Dipika		20.72		25.56
3.	Kusmunda		31.15	1.97	21.43
4.	Baroud		1.76		2.58
5.	Chhal		0.44		2.26
6.	Jampali		0.69		1.52
7.	Bijari		1.40		1.30
8.	Mahan-ii		2		2
	Total SECL		**95.71**	**1.97**	**86.99**
1.	Yekona i&ii		0.35		0.73
2.	Penganga		4.43		3.46
	Total WCL		**4.78**		**4.19**
1.	Sonepur bazari		6.50		6.06
2.	Raajmahal		0.51		0.04
	Total ECL		**7.01**		**6.1**
1.	Ashok		9.42		12.88
2.	Piparwar		3.09		1.13
3.	Birsa		1.75		1.62
4.	Amrapali		9.38		13.44
5.	Magadh		0.004		2.86
	Total CCL		**23.65**		**31.93**
Total CIL production (Mt)		**40.66**	**228.39**	**45.81**	**234.11**
		269.05		**279.92**	

2.2.2 Design and constructional features

SM, a compact machine, comprises a robust diesel engine, mechanical V-belt drive, and guide columns for transferring power to the cutting drum positioned in the middle of the machine, as depicted in Figure 2.3. It encompasses six primary units, namely, drive system, cutting drum unit, steering and lifting unit, undercarriage unit, lubrication system, and water sparkling system, with a sturdy framework ensuring stability during operations, especially when manoeuvring crawler tracks amidst significant cutting forces.

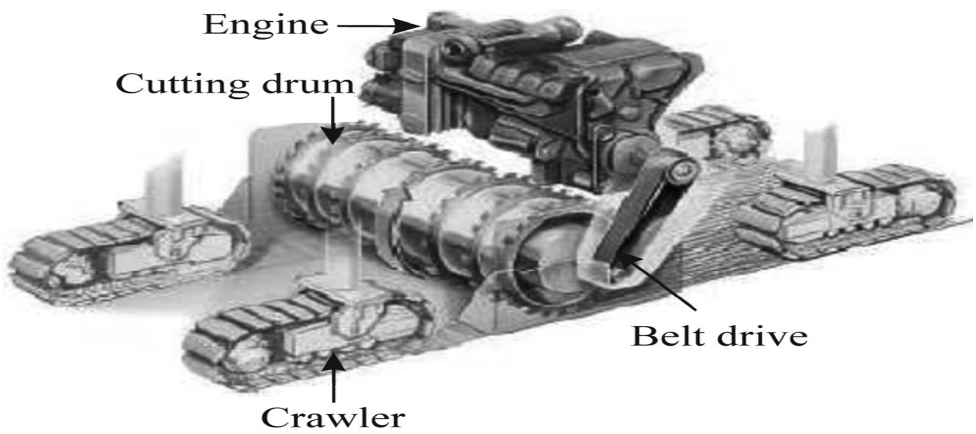


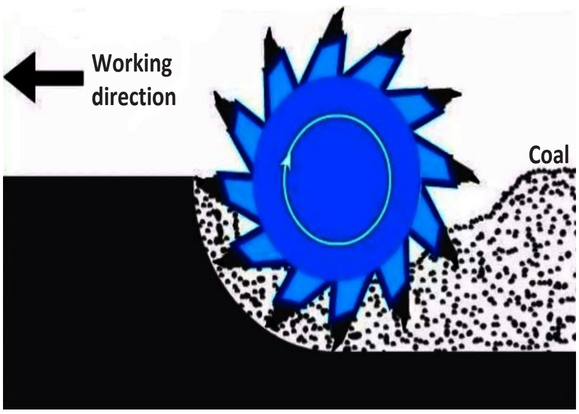
Figure 2.3: Schematic diagram for power transmission to the cutting drum of SM

Hydraulic cylinders facilitate the precise adjustment of crawlers and cutting drum. Advanced arrangements such as a side plate equipped with either sonic or cable sensor, multiplex, scan using grade wire, laser, and GPS allow for meticulous control of the cutting depth while cutting layers of specified thickness and generating specific surface profiles. The adjustable rotational speed of the SM cutting drum via belt pulley interchangeability, with automatic tensioning facilitated by hydraulic cylinders,. All hydraulic cylinders are sensor-controlled from the central unit. The system controlling central unit also provides engine overload protection via automatic speed reduction and machine lifting when operating along the boundary between coal seams and interbedded strata. Additionally, an integrated water sprinkling system, mounted on the drum housing, suppresses dust created during coal cutting and prolongs the pick’s lifespan by cooling off its tungsten carbide tip.

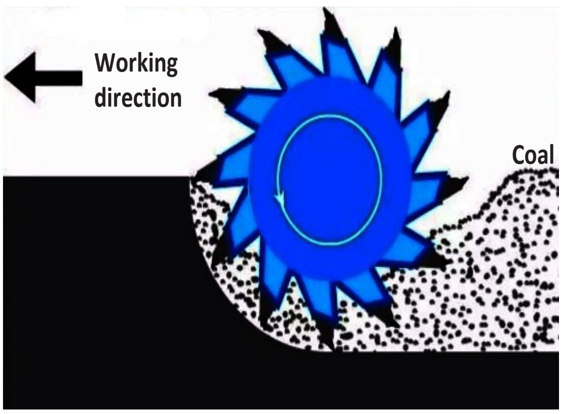
2.2.3 Cutting mechanism

The cutting drum of SM typically consists of special alloy steel featuring replaceable point-attack conical picks. These picks are secured through welded tool holders on the body of the drum. The tip of a conical pick is made of cemented (tungsten) carbide, fixed to a steel body by brazing process. The spiral ridges carrying these picks form a twin helix, directing the fragmented coal towards the drum centre for loading onto a conveyor or placement between the crawlers (Tatiya, 2005).

The cutting drum can rorate in two different cutting pathways: down-top and top-down, as shown in Figure 2.4. In down-top cutting, the drum rotates opposite to the direction of travel, starting from the bottom and penetrating to the top, allowing economical removal of coal from its seam. This type of cutting is generally preferred to cut brittle and fractured rock. The specific energy required for down-top cutting is 1.4 –1.8 times lower than that of top-down cutting (Väli, 2010). Consequently, middle cutting drum-type SM employs the down-top cutting pathway for coal mining.



a)



b)

Figure 2.4: Coal cutting pathways for SM: **a)** Down-top cutting; **b)** Top-down cutting

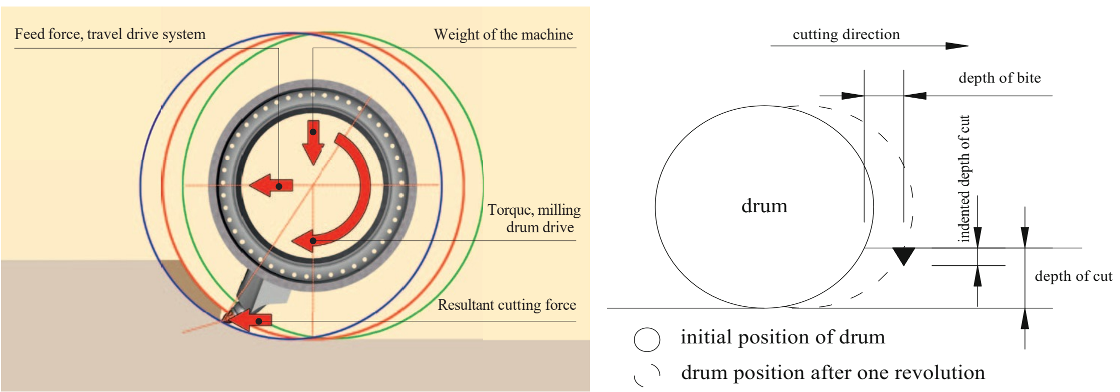
The cutting of coal using SM involves both linear and rotational motions of its cutting drum to produce discrete chips of coal, necessitating power utilisation in both cases

(Kumar *et al.*, 2020). The net resultant cutting force on the tip of a conical pick is a combination of three components, i.e., weight of the machine, torque of the cutting drum and feed force (travel drive system), as shown in Figure 2.5 (a). The resultant cutting force is responsible for initiating crack in the rock during cutting. The cutting force acts along the cutting direction. Normal force acts perpendicular to the surface and maintains the depth of pick penetration. Cutting force exerted by picks is a key factor for final coal production.

SM offers three depth forms for final production during coal cutting, namely, depth of bite, cutting depth, and indented cutting depth, as illustrated in Figure 2.5 (b). Depth of bite equals the tool's advance per drum revolution. Depth of cut refers to the coal thickness being cut. Indented depth of cut represents the depth at which a single pick penetrates the coal, which is calculated as given in Equation 2.1.

$$d = \frac{2V}{\pi v n_1} \qquad \text{(Equation 2.1)}$$

where d is the indented depth of cut, V is the cutting speed (m/min), ν is the drum speed (rpm), n_1 is the count of picks in the single cutting line.



a) b)

Figure 2.5: Schematic diagram of SM cutting drum: **a)** Forces acting during cutting process; **b)** Cut parameters during pick-coal interaction

2.2.4 Operating methods

SM operational techniques can be categorised into two distinct modes based on the on-site needs. The first category of the SM operation is classified as cutting mode, which is further divided into three types, namely, empty travel back method, turn back method, and continuous mining method, based on the path followed by the SM during the cutting of the entire bench width. The second category of SM operation is classified as loading mode, which is also further categorised into three types, namely, windrowing, direct truck loading, and sidecasting, based on the coal discharge system employed by the SM. All types of cutting and loading modes related to SM are described in detail as follows:

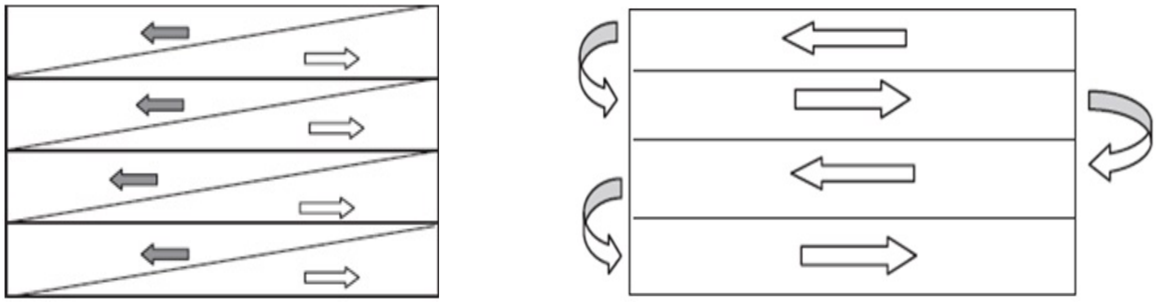
a) Cutting modes

i) Empty travel back method

In the empty travel back method, SM excavates a slice from one end of the bench to the other. Once a full slice is completed, the cutting drum is raised, and the SM travels back empty to the starting end without turning. It then prepares for a new cut in the adjacent parallel slice, as depicted in Figure 2.6 (a). This approach is suitable for narrow pits where the SM cannot turn, or turning takes longer than empty travel time.

ii) Turn back method

In this approach, the SM initiates cutting a slice from one end of the bench and progresses to the opposite end. The cutting drum is lifted once an entire slice is cut, and the SM turns back at the end of the slice. After that, it prepares for another cut to remove the adjacent parallel strip and then returns to the starting point, as shown in Figure 2.6 (b). This method is commonly employed when the machine's empty travel time is longer than its turning time. The productivity of SM in this type of cutting mode is relatively higher compared to the empty travel back method (Das, 2017).



a) b)

Figure 2.6: Cutting modes of SM: **a)** Empty travel back; **b)** Turn back

iii) Continuous mining method

SM adopts continuous mining method on a large, levelled coal bench to enable continuous coal cutting. The machine starts cutting from the entry point of the face. The method involves tracing the face perimeter and navigating gentle turns as needed without raising the cutting drum to ensure uninterrupted cutting. Upon completing the initial elliptical stripping slice, it cuts the adjacent one. This cycle continues until the elliptical turns become too acute for continuous cutting, as depicted in Figure 2.7. This method stands out as the most productive approach employed by SM. However, SM employs the turn back method to extract the remaining coal at the center of face. Although overlapping elliptical movements can mitigate cutting breaks, productivity declines in these overlapping regions.

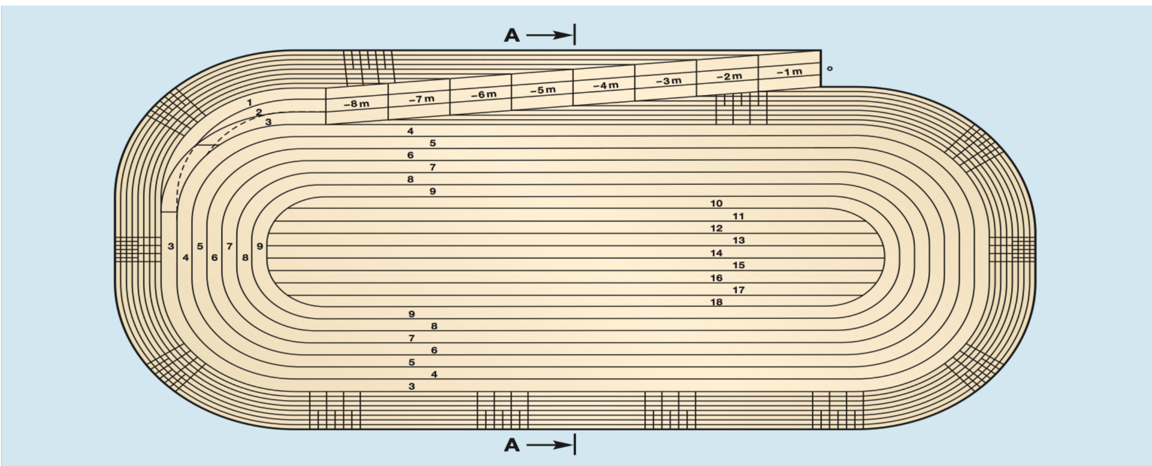


Figure 2.7: Continuous mining method for surface miner (Wirtgen, 2008)

b) Loading modes

i) Windrowing

In windrowing mode, the SM deposits the excavated coal directly behind the machine, positioned between the crawlers, without relying on a conveyor. However, the material requires subsequent handling by a front loader. This setup separates the cutting process from loading activities and provides better selectivity, especially at inclined coal seams.

ii) Direct conveyor loading

By operating SM in direct loading mode, they can load the cut coal directly onto trucks via an integrated discharge conveyor. The conveyor can slew to either side, and the discharge height can be modified to match the height of the transport vehicles. The counterweight balances the conveyor weight. In this method, fragmented coal does not require additional re-handling, hence, becomes least prone to absorb moisture from the ground. However, this method encourages the long and wide faces for better manoeuvring of dumpers.

iii) Sidecasting

Sidecasting mode creates a coal stockpile by depositing excavated coal from multiple strips onto a heap using an integrated discharge conveyor. As the SM moves forward, the primary conveyor picks up the excavated coal in the drum housing and places it on the discharge conveyor. Coal can be piled up continuously for 3 to 5 adjacent strips depending on its slewing angle, for loading dumpers using front-end loaders. However, this method limits coal cutting on either side of the stockpile.

2.2.5 Rated production capacity

Production is the hourly coal movement rate (Caterpillar, 2008). Table 2.3 presents the mathematical expressions to evaluate theoretical coal production of SM operating in various cutting and loading modes.

Table 2.3: Theoretical coal production for SM in different operating methods

Loading mode→ /Cutting mode↓	Windrowing	Sidecasting	Direct Conveyor loading
Empty travel back method	$Q_T = \frac{S \times L \times D \times 60}{\frac{L}{V} + \frac{L}{V_e}}$	$Q_T = \frac{S \times L \times D \times 60}{\frac{L}{V} + \frac{L}{V_e}}$	$Q_T = \frac{S \times L \times D \times 60}{\frac{L}{V} + \frac{L}{Ve} + [\frac{S_t}{V_t} \times \left(\frac{S \times D \times L \times S_f}{Q_d \times F_f}\right)]}$
Turn back method	$Q_T = \frac{S \times L \times D \times 60}{\frac{L}{V} + \frac{(2\pi R + 2.5l)}{V_e}}$	$Q_T = \frac{S \times L \times D \times 60}{\frac{L}{V} + \frac{(2\pi R + 2.5l)}{V_e}}$	$Q_T = \frac{S \times L \times D \times 60}{\frac{L}{V} + \frac{(2\pi R + 2.5l)}{V_e} + [\frac{S_t}{V_t} \times \left(\frac{S \times D \times L \times S_f}{Q_d \times F_f}\right)]}$
Continuous mining method	$Q_T = S \times D \times V \times 60$	$Q_T = S \times D \times V \times 60$	$Q_T = \frac{S \times L \times D \times 60}{\frac{L}{V} + [\frac{S_t}{V_t} \times \left(\frac{S \times D \times L \times S_f}{Q_d \times F_f}\right)]}$

where, Q_T is the theoretical coal production (bm^3/h), S is the centre to centre spacing between adjacent cuts (m), D is the cutting depth (m), L is the total length of cut (m), V is the linear speed of SM during cutting (m/min), V_e is the linear speed of SM during marching (m/min), R is the turning radius of SM (m), *l* is the total length of SM (m), S_t is the minimum distance between two dumpers while changing for loading (m), V_t is the average speed of dumper (m/min), Q_d is the rated capacity of dumper (m^3), F_f is the fill factor, and S_f is the swell factor.

2.3 Production and productivity

Mechanical excavators like continuous miner (Roxborough *et al.,* 1981), roadheader (Deshmukh *et al.,* 2019), shearer (Hu *et al.*, 2018), shovel (Fisonga and Mutambo, 2017), bucket wheel excavator (Seroshtan, 1971), and surface miner (Dey and Ghose, 2011) gained popularity for producing discrete chips of coal in underground and opencast mines, respectively. Production is a process of combining various material resources (stuff) and immaterial resources (plans) to make something for consumption (the output). Production, defined broadly, entails creating new goods and services through the utilisation of resources

(Eğilmez, 2016; Songur and SaraçElmas, 2017). Resources, termed as production factors, enable the production process. The methods of combining the production factors in the process of making output are called technology or total factor productivity. In neoclassical economics, the transformation of these production factors into output is symbolised by a mathematical expression known as production function.

Production functions are used as a measure of productivity. Productivity is a term first used in the 1870's with the introduction of the marginal utility theory, which is defined as the quotient obtained by dividing output by one of the production factors (Organisation for European Economic Co-operation, 1950). Scharf (1984) recommended a system approach, defining productivity as the ratio of output achieving system function to all the production factors consumed. Weihrich and Koontz (1993) specified it as "the output-input ratio within a time interval with due consideration for quality." Since, improved productivity implies greater output relative to input growth, therefore, adopting an effective productivity measurement index is crucial for measuring technology improvement vis-à-vis accommodating changes in goals and policies over time.

Equation 2.2 describes a coal production function in terms of production factors, such as, machine, capital, energy and technology (Singh *et al.*, 2023a). Thus,

$$Q \propto f(M, K, E, A) \qquad \text{(Equation 2.2)}$$

where, Q is the coal production (t), M is the machine (h), K is the capital (₹), E is the energy (J), and A is the technology coefficient or total factor productivity.

2.4 Energy productivity

Energy productivity is a single factor productivity index, which can be used to characterise excavators. It is measured as an output-input ratio of coal production to energy consumed for coal cutting within a time interval with due consideration for quality. It depends on how energy is effectively utilised in its conversion into finished product. Energy productivity can be expressed using Equation 2.3.

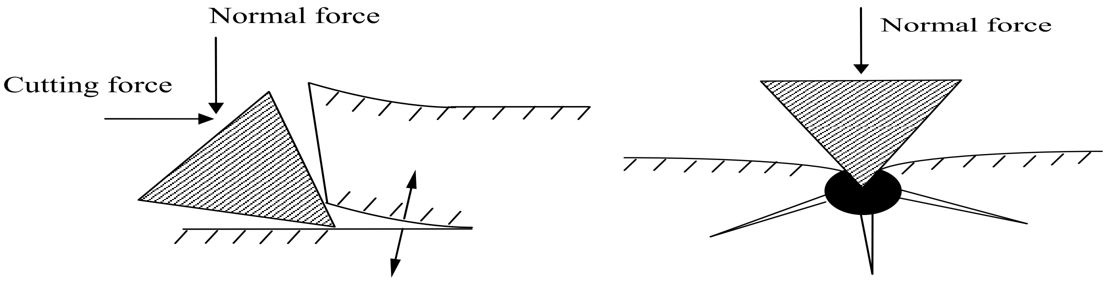
$$A_E = \frac{\text{Coal production}}{\text{Energy consumption}} = \frac{Q_T}{3.6P_T} \qquad \text{(Equation 2.3)}$$

where, A_E is the energy productivity of an excavator during coal cutting (bm^3/MJ), Q_T is the theoretical coal production (bm^3/h), P_T is the total power required to cut coal (kW).

2.4.1 Mechanics of coal cutting

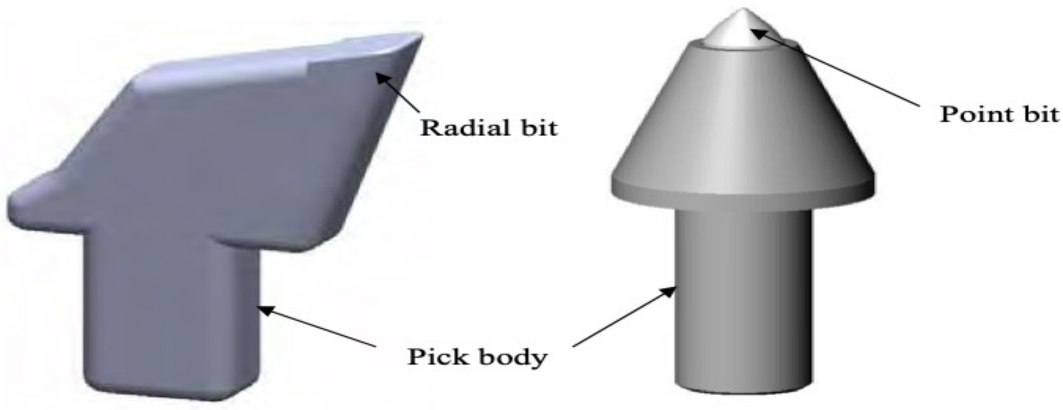
Different cutting tools are used in mechanical excavation of rocks and can be categorised based on their actions, with drag bits hitting coal parallel to the seam and indenters breaking coal by pressing perpendicularly into the seam, as shown in Figures 2.8 (a) and (b). The Research and Development Establishment for Coal Mining investigated rock cutting principles and cutting tool performances, focusing on enhancing productivity of excavators with low wear (Hurt and Laidlaw, 1979; Hurt and Evans, 1981; Hurt and MacAndrew, 1985). The results showed that the drag bits were limited for cutting soft to medium-hard rocks with low abrasiveness due to high breakage susceptibility and wear on the front edge than indenters when cutting hard rocks (Powell, 1991; Tiryaki, 2004).

Drag bits are further classified into radial bits resembling a chisel or wedge shape and point bits possessing a conical shape, having its axis aligned with the pick body and angled to the cutting direction, as depicted in Figures 2.9 (a) and (b). Among these, conical picks proved consistently more productive in terms of energy at deeper cutting depths (Roxborough *et al.*, 1981; Sundae and Myren, 1987; Bilgin *et al*., 2006). Additionally, the shape of a conical pick remains sharp due to the uniform symmetrical wear of the cutting tool, leading to a longer life than chisel-shaped picks (Khair, 2001; Dewangan, 2016).



(a) (b)

Figure 2.8: Types of cutting tool: **a)** drag bit; **b)** indenter

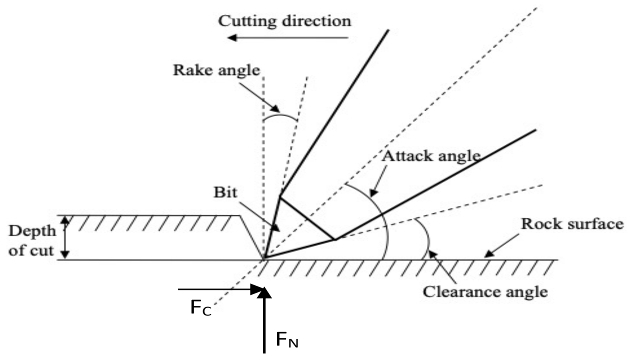


(a) (b)

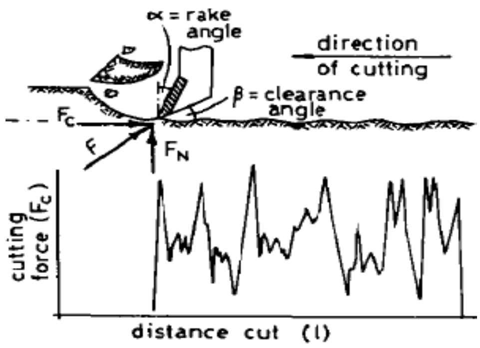
Figure 2.9: Types of drag bit: **a)** radial bit; **b)** point bit

Picks serve two functions: initiating breakage ahead and profiling to clear a path through the remaining material in the sloping surface left by a major breakage (Hurt and Evans, 1981). As the pick presses into the coal, elevated contact compressive stresses arise in the intact part of the coal seam beneath the point bit, generating the resultant cutting force responsible for initiating breakage and ejecting coal due to friction and wear (Pozin *et al*., 1989). The force's axis is angled with the cut surface to optimise normal and tangential components for efficient cutting, called an attack angle. A conical pick displayed minimal cutting force at a 50° attack angle, corresponding to a 12° back clearance angle (Cigla and Ozdemir, 2000). Cutting geometry of a conical pick is depicted in Figure 2.10a.

When cutting force surpasses coal strength, it initiates and propagates cracks laterally into the coal seam through the free surface. In the final stage, coal fragmentation occurs when the main crack reaches the surface again (Tiryaki and Dikmen, 2006). When a large coal chip is torn with the ejection of finely pulverised coal from the seam, cutting force peaks from zero, at which the failure happens, before dropping back to zero or near zero, as shown in Figure 2.10b. Meanwhile, if the fracture leading to the tearing has partly extended inside the brittle coal seam, the cutting force remains zero or near zero until the pick covers the length of the fracture (Rojek, 2007).



(a)



(b)

Figure 2.10: Schematic view of conical pick during coal cutting: **a)** cutting geometry; **b)** variation in cutting force (Roxborough *et. al.*, 1981)

2.4.2 Assessment of cutting force

There are limited theories on mechanical coal cutting. According to the theory of Evans (1961) on coal cutting by chisel picks:

i) A cutting tool gains initial entry into the rock because of stress concentration under a sharp edge.

ii) Stress concentration is generated from due to the mechanical properties of the rock during cutting.

iii) Stress initially causes frictional crushing and elastic deformation until the stress exceeds the rock strength, and rupture eventually occurs.

Evans (1965) expressed that failure takes place in the coal due to tensile stress along the circular curve ab, as shown in Figure 2.11. Meanwhile, friction was presumed as non-existing between picks and coal. The crack initiates from the tip of the cutting tool. The cutting force F acts on the failure chip which is perpendicular to the pick surface ac. The pick gives up the position at point ‘a’ and moves to point ‘b’. The chip of the coal rotates about the point b and force again acts at point b. The cutting force was calculated from the chip’s equilibrium and considering moments around the point b, as given in Equation 2.4.

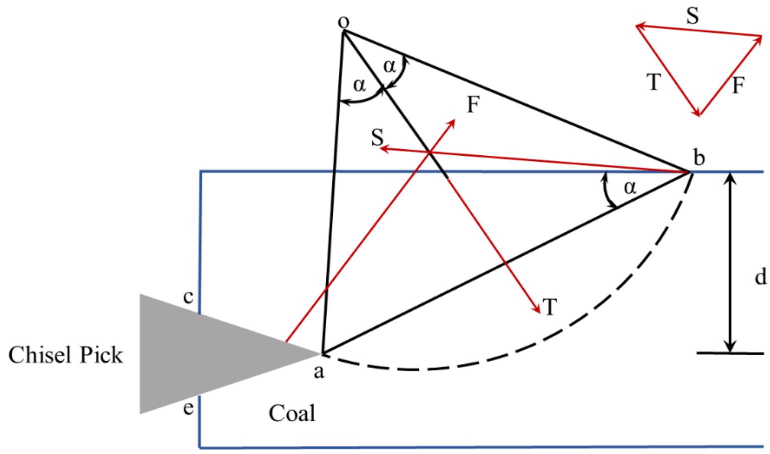


Figure 2.11: Schematic view of tensile breakage mechanism (Evans, 1965)

The discontinuous formation of chips is seen during coal cutting process due to the rapid oscillations of the cutting force. Figure 2.12 depicts the theory of Nishimatsu (1972) on the cycle of coal cutting process by chisel picks. A crushed zone is generated at the edge of the cutting tool during the pushing of a tool initially. The crushed zone is forced oppose to the rake face of the tool during pushing the cutting tool deeper; this zone is known as the primary crushed zone. As the cutting tool tip goes into depth, the value of cutting force increases. A specific value of penetration depth originates stress which is reason of crack propagation and converts into the formation of the coarse cutting chip and the secondary crushed zone starts at the time. Finally, the cutting tool moves into the overcutting zone for profiling of the groove, and a new cycle of rock cutting process starts again for chipping.

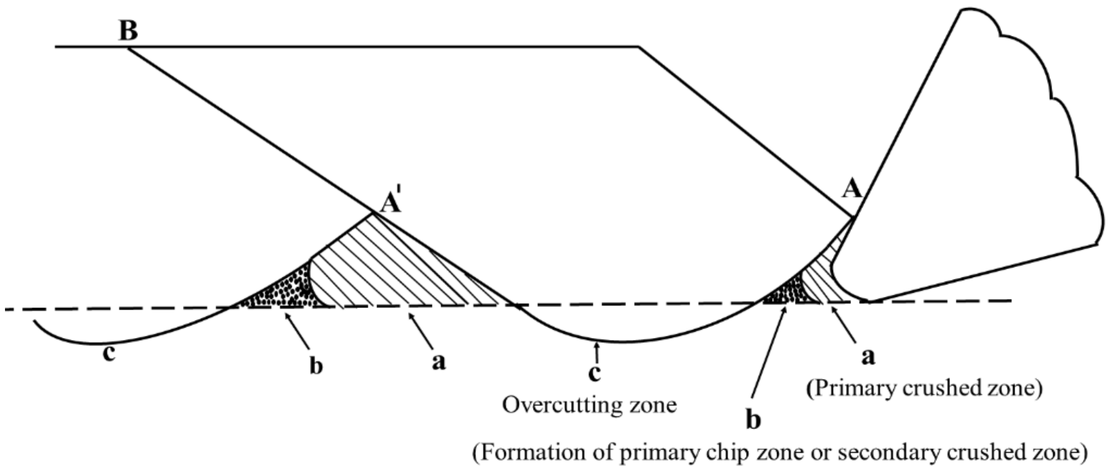


Figure 2.12: Cyclic process of rock cutting (Nishimatsu, 1972)

It relies on the criterion of failure, cutting depth and the pick's geometry. It is presumed that the failure occurs owing to shear stress only which represents line ab as shown in Figure 2.13. The stress distribution decreases from the pick edge point a to the surface point b due to the higher stress concentration at the tip of the pick. The cutting force was derived at the equilibrium state of resultant force F and the addition of resultant stress S. Equation 2.5 presents cutting force model developed by Nishimatsu (1972).

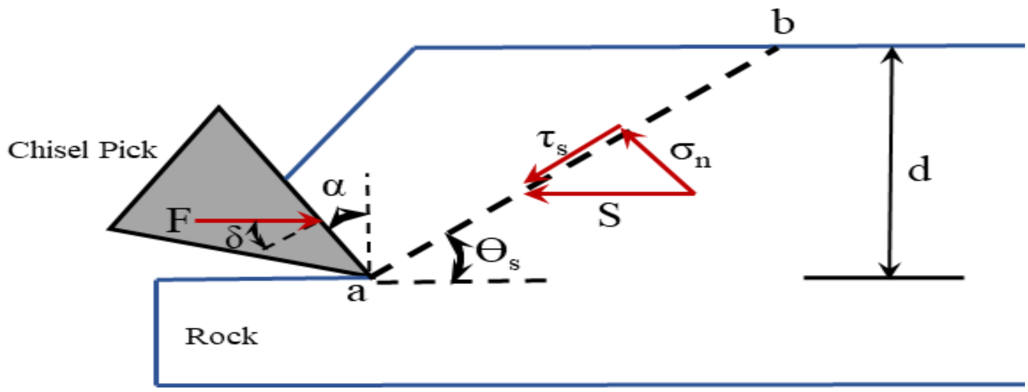


Figure 2.13: Schematic view of shear breakage mechanism (Nishimatsu, 1972)

Several researchers have developed mathematical expressions to determine cutting force during pick-coal interactions using theoretical and experimental methods. Table 2.4 discusses the cutting force models with key features and limitations. The previous model of Evans (1965) and Nishimatsu (1972) were two-dimensional models. However, Evans (1984) proposed that cutting mechanism of the conical pick is a 3-dimensional process and modified his previous model by considering both the tensile strength and compressive strength of the coal (Ranman, 1985; Fowell, 1993). It is assumed that radial compressive stresses are produced along with tensile hoop stresses during penetration of a conical pick. When the stress equals to the tensile strength of coal; cracks start to propagate and the chip in a V-shape is formed. The coal chip is symmetrical about the central line. The force was calculated on the half section of the chip. The tensile force ($T = \sigma_t d/\cos\phi$) is perpendicular to the surface OB, as shown in Figure 2.14. The cutting force was calculated using mathematical integration of elementary area of the chip.

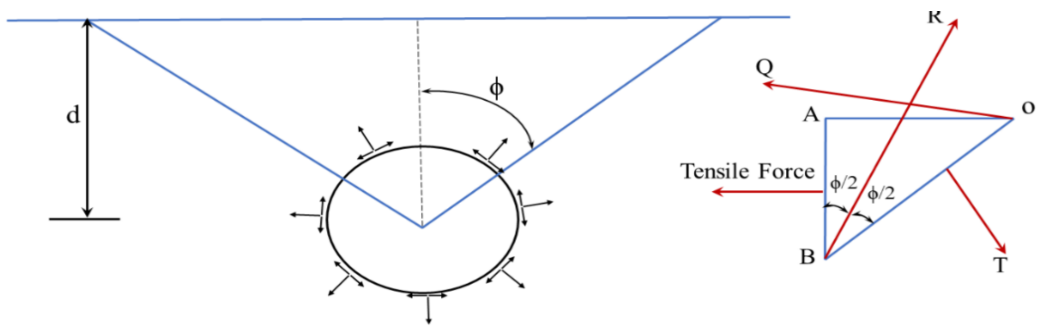


Figure 2.14: Schematic view of modified cutting mechanism (Evans, 1984)

Roxborough and Liu (1995) modified Evans' theory for conical picks, as depicted in Equation 2.7. Goktan (1997) also suggested an alternative theory for conical picks, emphasising that cutting force is not inversely proportional to coal compressive strength, as shown in Equation 2.8. Moreover, Goktan and Gunes (2005) evaluated cutting force for conical picks based on the experimental results, which mainly relies on the pick's geometry, criterion of failure, cutting depth and tensile strength of coal, as described in Equation 2.9.

Su and Akcin (2011) experimentally studied and numerically modelled the mean peak cutting force for conical picks using discrete element method. The numerical results were compared with experimental results and developed theoretical models by several researchers. Relationship of models investigated with regression analysis. Numerical test results depicted strong correlations with Goktan and Gunes (2005) cutting force model.

Table 2.4: Cutting force models developed for different picks during coal cutting

Researcher, Year	**Pick**	**Cutting force equation, (Equation number)**	**Study domain with key features and limitations**
Evans, 1965	Chisel	$F_C = \frac{2\sigma_t dw \sin\frac{1}{2}\left(\frac{\pi}{2}-\alpha\right)}{1-\mathrm{Sin}\frac{1}{2}\left(\frac{\pi}{2}-\alpha\right)}$, (Equation 2.4)	♦ Cutting force was estimated for wedge cutting tool in coal. ♦ The failure is due to tensile stress exceeding tensile strength. **Limitation:** ♦ Effect of friction was not considered between cutting tool and coal.
Nishimatsu, 1972	Chisel	$F_c = \frac{2\sigma_s d\, w \cos(\psi-\alpha)\cos(i)}{(n+1)[1-\sin(i+\psi-\alpha)]}$, (Equation 2.5)	♦ Cutting force was estimated by following Merchant's metal cutting theory. ♦ The crack initiation and growth satisfy the Mohr Coulomb's failure criterion.
Evans, 1984	Conical	$F_c = \frac{16\pi\, d^2\, \sigma_t^2}{\sigma_c \cos^2\left(\frac{\phi}{2}\right)}$, (Equation 2.6)	♦ This is the initial theory of coal cutting for conical pick. ♦ The equation was developed considering the coal parameter such as, UCS and TS and depth of cut and semi-cone angle. **Limitations:** ♦ The influence of friction between coal and tool was ignored. ♦ The cutting force doesn't reduce to zero with zero cone angle. ♦ Practically proven that UCS is directly proportional to cutting force. However, model considers UCS inversely proportionated with cutting force. ♦ This equation provides very less values as compared to experimental values.
Roxborough and Liu, 1995	Conical	$F_c = \frac{16\pi\, \sigma_c\, d^2 \sigma_t^2}{\left[2\sigma_c+\left(\sigma_c \cos\left(\frac{\phi}{2}\right)\right)\left(\frac{1+\tan\psi}{\tan\left(\frac{\phi}{2}\right)}\right)\right]^2}$, (Equation 2.7)	♦ The effect of the friction is considered along with UCS and TS. **Limitation:** ♦ The cutting force reduces with increasing values of cutting depth like Evans equation.

Goktan, 1997	Conical	$F_c = \frac{4\pi\sigma_t d^2 \sin^2(\frac{\phi}{2}+\psi)}{\cos(\frac{\phi}{2}+\psi)}$, (Equation 2.8)	♦ Deficiencies of Evans equations are removed. ♦ Tensile strength is taken for calculating the cutting force. **Limitations:** ♦ Friction was taken directly resulting in higher forces at higher cutting depth. ♦ Only one friction angle of 10° was used for all rocks.
Goktan and Gunes, 2005	Conical	$F_c = \frac{12\pi\sigma_t d^2 \sin^2[\frac{1}{2}(90-\alpha)+\psi]}{\cos[\frac{1}{2}(90-\alpha)+\psi]}$, (Equation 2.9)	♦ Cutting force equation considered the asymmetric nature of cutting action. ♦ Gives more realistic prediction considering rake and friction angle. **Limitations:** ♦ Mode of failure for different rake angles not defined. ♦ Only one friction angle of 10° was considered for rocks with different properties and strength.
Yasar, 2020	Conical	$F_c = kk_r \varepsilon d\sigma_c A(\alpha)B(\beta)$, (Equation 2.10)	♦ A semi-empirical model considering geometrical orientation of cutting tool. ♦ The whole study was based on brittleness of the rock and k as universal constant, which is the which is the ratio of maximum cutting force to mean cutting force. **Limitations:** ♦ The cutting force equation is dimensionally unbalanced. ♦ The cutting speed is neglected while cutting the rock.
Legends: F_c = cutting force (kN) σ_t = rock tensile strength (MPa) σ_s = rock shear strength (MPa) σ_c = rock compressive strength (MPa) w = width of the tool (mm) ϕ = tip angle (degree) d = cutting depth (cm) α = rake angle (degree) β = clearance angle (degree) ψ = friction angle between pick and coal (degrees)			n = stress distribution factor = $12-(\frac{\alpha}{5})$ i = rock internal friction angle (degree) k = ratio of maximum and minimum cutting force k_r = Reduction constant (0.72 for relieved cutting and 1 for unrelieved cutting) ε = Empirical constant $A(\alpha)$ = Rake angle function $B(\beta)$ = Clearance angle function

2.4.3 Energy productivity models – a review

Energy productivity reciprocates specific energy, which is defined as the work done to excavate a unit volume. Many scientists and researchers have been studied the specific energy as a direct indicator of conical pick's productivity during cutting of high strength rocks (Fowell and Ochei, 1984; Ceylanoğlu, 1991; Mishnaevsky, 1995; Khair, 1996; Hood and Alehossein, 2000; Inyang, 2002; Balci and Bilgin, 2007). Pasamehmetoğlu *et al.* (1992) evaluated the energy productivity for the classification of power shovels during lignite cutting in opencast mines. Achanti and Khair (2001) studied the energy productivity of continuous miner during coal cutting in underground mines. Mezyk *et al.* (2016) proposed that energy required for rock cutting by cutting drum of continuous miner relies on power, speed and cutting depth. Zhao *et al.* (2019) studied the drum design for coal cutting based on ANSYS/LS-DYNA simulation and optimised the parameters using genetic algorithm. The load on drum was calculated at different conditions, which revealed that the effect of traction speed was greater than rotational speed on drum's load. Cutting power (Gunes *et al.*, 2007), cutting depth (Roepke and Hanson, 1984) and cutting speed (Balci *et al.*, 2023) crucially affect energy productivity during pick-coal interactions. It increases with increased cutting depth (Miller and Sikarskie, 1968; Bilgin *et al.*, 2006).

Detailed rock cutting tests with analytical and numerical simulations, however, showed that energy productivity is not only a function of machine specifications, but it is also closely related to tensile strength of coal (Dunn *et al.*, 1993; Murthy *et al.*, 2008). Tiryaki and Dikmen (2006) provided insights for the same relationship at a laboratory-scale linear cutting of rock by conical picks, as given in Equation 2.11.

$$E = 1/\,(0.67 + 3.12\sigma_t) \qquad \text{(Equation 2.11)}$$

where, E is the energy productivity (m^3/MJ), and σ_t is the rock tensile strength (MPa).

2.5 Machine productivity

Machine productivity, as another single factor productivity index, is used in the selection of mechanical excavators in terms of cutting time. It can be measured as an output-input ratio of coal production to actual time utilised by an excavator for coal cutting with due consideration for case specific ancillary times, as well as times for manoeuvring, changing trucks and other operationally necessary ancillary times in the excavator's scheduled shift time in opencast mines. It depends on how scheduled shift time is effectively utilised in its conversion into fragmented coal. This index can be expressed using Equation 2.12.

$$A_M = \frac{\text{Coal production}}{\text{Cutting time}} = \frac{Q_T}{C_T} \qquad \text{(Equation 2.12)}$$

where, A_M is the machine productivity (bm^3/h), Q_T is the theoretical coal production (bm^3/day), C_T is the cutting time of an excavator in its scheduled shift time (h/day).

2.5.1 Machine productivity models – a review

The productivity models of continuous coal cutting and milling machines are reviewed to explore the role of critical factors under varied geo-mining conditions. Minor variations in rock properties can detrimentally impact the productivity of mechanical excavators (McFeat-Smith and Fowell, 1977). Productivity loss can reduce the overall coal production below the techno-economic viability threshold, thereby negating the purpose of deploying machines in an excavation system. Therefore, it is essential to acknowledge the limitations inherent in the use of empirical classification charts and prediction models to evaluate the machine productivity of excavators in opencast coal mines.

Empirical classification charts and prediction models based on the combination of numerous geotechnical and physicomechanical properties of rock mass and technical specifications of machine have been developed by different researchers to evaluate the machine productivity in laboratory scale and field scale to make site-specific recommendations (Farmer, 1986; Bilgin *et al.*, 1988 and 1997; Gehring, 1992; Jones and Kramadibrata, 1995; Kramadibrata and Shimada, 1996; Foster *et al.*, 2004; Bhatt, 2006; Murthy *et al.*, 2009; Dey and Ghose, 2011; Origliasso *et al.*, 2014; Prakash *et al.*, 2015). Central Mine Planning and Design Institute, India (CMPDI) uses a norm to evaluate the SM productivity during coal cutting. These models are reviewed as follows:

a) Farmer (1986)

Farmer (1986) introduced the DOSCO-IIIA roadheader productivity model based on the energy index curve, as given in Equation 2.13.

$$L = \frac{N\eta}{EI} \quad \text{(Equation 2.13)}$$

where, L is the machine productivity (bcm/h), N denotes the machine power (kW), η signifies the efficiency, and EI represents the energy input.

b) Bilgin et al. (1988; 1997a, b)

Bilgin *et al.* (1988) developed a rock mass cuttability index by correlating uniaxial compressive strength and rock quality designation to predict the advance rate of excavators with a rated power of not more than 100 HP, as given in Equations 2.14 and 2.15.

$$RMCI = \sigma_c \left(\frac{RQD}{100}\right)^{\frac{2}{3}} \quad \text{(Equation 2.14)}$$

$$AR = 28.06 \times 0.997^{RMCI} \quad \text{(Equation 2.15)}$$

where, RMCI denotes the rock mass cuttability index, AR is the advance rate (bm^3/h), σ_c states the uniaxial compressive strength (MPa) and RQD is the rock quality designation.

Bilgin *et al.* (1997a, b) performed linear cutting tests using a full-sized cutting tool on large stone blocks (70 x 50 x 50 cm^3) in laboratory conditions to record the cutting performance.

Equation 2.16 depicts the instantaneous cutting rate of excavators.

$$\text{ICR} = 0.28 \times \text{P} \times 0.974^{\text{RMCI}} \qquad \text{(Equation 2.16)}$$

where ICR denotes the instantaneous cutting rate (m^3/h), P is the rated cutting power (kW), RMCI represents the rock mass cuttability index.

c) Gehring (1992)

According to Gehring (1992), the production performance of a Voest Alpine Roadheader can be described by Equation 2.17.

$$\text{L} = \frac{\text{kN}_\text{c}}{\sigma_\text{c}} \qquad \text{(Equation 2.17)}$$

where, L represents the production performance (bcm/h), k denotes the factor for consideration of relative cuttability or tuning effect between cutting machine and rock, N_c states the cutter head power (kW), σ_c denotes uniaxial compressive strength (MPa).

Later, he considered the other factors like cutting action and modified his earlier formula, as given in Equation 2.18.

$$\text{L} = \frac{\text{k}_1\text{k}_2\text{k}_3\text{N}_\text{c}}{\sigma_\text{c}} \qquad \text{(Equation 2.18)}$$

where, k_1 is the relative cuttability of intact rock (6 for very tough and plastic rock, 7 for tough and or plastic rock, 8 for average rock, 9 for brittle rock but not plastic, 10 for very brittle but not plastic rock, 10–15 for coal); k_2 is the influence of discontinuities (1 for massive rock without the influence of fabric with discontinuity spacing > 25 cm, 1.5–2 for layered or fissured rock with average discontinuity spacing 10–25 cm and rock with partially closed bedding planes, 2.5 for layered or fissured or interbedded rock with average discontinuity spacing < 5 cm and no layer thicker than 10 cm vis-à-vis no discontinuities fully open), k_3 is the influence of specific cutting conditions related to machine such as, pick array and pick shape.

d) Jones and Kramadibrata (1995)

Jones and Kramadibrata (1995) proposed a logarithmic relationship between SM productivity and uniaxial compressive strength of rock, as given in Equation 2.19. It should be noted that the equation is limited up to 60 MPa of rock strength.

$$L = 1005 - [559 \times \ln(\sigma_c)] \qquad \text{(Equation 2.19)}$$

where L represents the production rate (m^3/h), σ_c represents the uniaxial compressive strength of rock sample (MPa).

e) Kramadibrata and Shimada (1996)

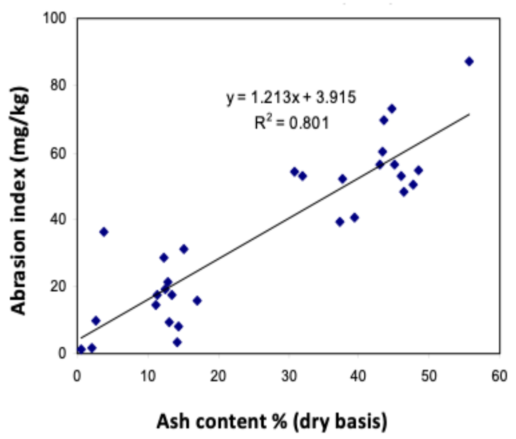
Kramadibrata and Shimada (1996) demonstrated a correlation between Rock Cuttability Index for SM (RCI) and various intact rock, rock mass and machine-related factors as represented in Equation 2.20.

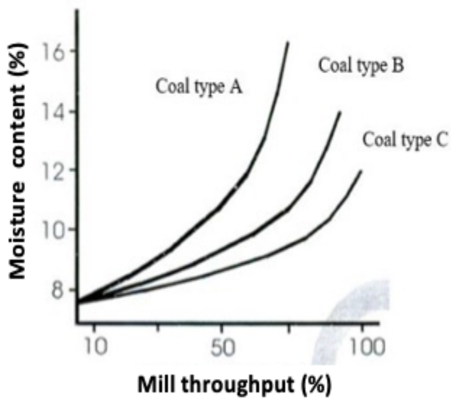
$$L = \left(\frac{N}{RCI\sigma_c}\right) \propto f\left(\left(\frac{\gamma\delta}{\sigma_c}\right), \left(\frac{\sigma_t}{\sigma_c}\right), \left(\frac{d}{\delta}\right), \left(\frac{E}{\sigma_c}\right), \left(\frac{F}{\delta\sigma_c}\right)\right) \qquad \text{(Equation 2.20)}$$

where L represents the production rate (m^3/h), N denotes the rated machine power (kW), σ_c represents the uniaxial compressive strength of rock sample (MPa), γ denotes the specific weight (kN/m^3), δ represents the discontinuity spacing (m), E denotes the Young's modulus (MPa), F represents the Schimazek's abrasivity factor (N/mm), and σ_t denotes the tensile strength of rock sample (MPa).

f) Foster et al. (2004)

Foster *et al.* (2004) conducted a study to measure machine productivity of grinder based on abrasion index in terms of grinding material consumption. This study shows the effect of ash content and moisture content on abrasion index with special reference to coal milling, as shown in Figure 2.15 (a). The summary of the erosion test results is given in Table 2.5.





(a) (b)

Figure 2.15: Effect of coal properties on productivity of coal mills: **a)** abrasion index against ash content of coal; **b)** moisture content against mill throughput

Table 2.5: A summary of standard erosion test results on the pulverised coal samples

S. N.	Parameter	Coal A	Coal B
1	Moisture content of pulverised coal (%)	3.9	2.9
2	Ash content of pulverised coal (%, dry basis)	11.2	8.8
3	Consumption rate for pulverised coal (mg/kg of coal)	0.91	0.47
4	Consumption rate for pulverised coal (mg/kg of ash)	8.49	5.44
5	Consumption rate for pulverised coal ash (mg/kg)	9.65	7.6

g) Bhatt (2006)

Bhatt (2006) demonstrated the impact of ash in coal at various moisture content on the productivity of mills at coal-fired thermal power plants, as illustrated in Figure 2.15 (b). The effects of varying ash content in coal, from 6% to 75%, on different mechanical components were modelled using experimental data. Among the fans and mills, the abrasion effects of coal with 75% ash content account for 20% of the specific energy consumption of induced draft fans, 10%-12% of that of forced draft and primary air fans, and 17% of that of drum mills. It also accounted for a 5%-6% decrement in fan productivity.

h) Murthy et al. (2009)

Murthy *et al.* (2009) proposed a cuttability index for SM (CISM) based on rock mass factor, intact rock factor, and machine factor to predict machine productivity, as given in Equations 2.21 and 2.22. However, it was assumed that 1/6th of the circumferential length of the drum gets engaged in rock cutting.

$$\mathrm{NTPH} = \mathrm{b_0(CISM)^{b_1}} \quad \text{(Equation 2.21)}$$

$$\mathrm{CISM} = \frac{\mathrm{MF}}{\mathrm{RMF \times IRF}} \quad \text{(Equation 2.22)}$$

where, RMF is the rock mass factor and equates to rock mass P-wave velocity (km/s), MF states the machine factor, as shown in Equation 2.23, and IRF stands for the intact rock factor, as given in Equation 2.24.

$$\mathrm{MF = EP \times CS \times CA} \quad \text{(Equation 2.23)}$$

$$\mathrm{IRF = LV_P \times SiO_2} \quad \text{(Equation 2.24)}$$

where, LV_p represents the laboratory P-wave velocity (km/s), SiO_2 denotes the silica content (%), EP is the engine power (kW), CS states the cutting speed (m/s), CA is the instantaneous cutting area engaged during rock cutting (m^2), NTPH is the production (t/h), b_0 and b_1 are constants.

i) Dey and Ghose (2011)

Dey and Ghose (2011) formulated a new cuttability index for SM (CI) based on the combined rating of five parameters, *i.e.*, point load index, volumetric joint count, abrasiveness, direction of cutting with respect to major joint direction, and machine power, as given in Equation 2.25. Ratings of these parameters are tabulated in Table 2.6 and corresponding technical feasibility can be appraised from guidelines provided in Table 2.7.

Table 2.6: Rating of parameters of cuttability index for surface miners

Class	**I**	**II**	**III**	**IV**	**V**
Point load index (I_{S50}) Rating (I_S)	< 0.5 5	0.5–1.5 10	1.5–2.0 15	2.0–3.5 20	> 3.5 25
Volumetric joint count (no./m^3) Rating (J_V)	> 30 5	30–10 10	10–3 15	3–1 20	1 25
Abrasivity Rating (A_W)	< 0.5 3	0.5–1.0 6	1.0–2.0 9	2.0–3.0 12	> 3.0 15
Cutting direction with respect to the major joint Rating (J_S)	72°–90° 3	54°–72° 6	36°–54° 9	18°–36° 12	0°–18° 15
Machine power (kW) Rating (M)	> 1000 4	800–1000 8	600–800 12	400–600 16	< 400 20

Table 2.7: Cuttability index and expected surface miner performance

CI	50 > CI	50 < CI < 60	60 < CI < 70	70 < CI < 80	CI > 80
Surface miner performance	Very easy excavation	Easy excavation	Economic excavation	Difficult excavation, not economic	It should not be deployed

$$\mathrm{CI} = \mathrm{I_S} + \mathrm{J_V} + \mathrm{A_W} + \mathrm{J_S} + \mathrm{M} \qquad \text{(Equation 2.25)}$$

where, I_S, J_V, A_W, J_S, and M represent the rating corresponding to point load index, volumetric joint count, abrasivity, direction of cut with respect to major joint orientation and machine power, respectively.

The productivity of SM was evaluated using Equation 2.26.

$$\mathrm{L} = \left(1 - \frac{\mathrm{CI}}{100}\right) \mathrm{kM_c} \qquad \text{(Equation 2.26)}$$

where, L is the productivity of SM (bm^3/h), M_c denotes the rated capacity of machine (bm^3/h), CI states the cuttability index, k represents the factor for consideration of influence of specific cutting condition and is a function of pick lacing, pick shape etc., ranging from 0.5 – 1.0 for SM.

j) Origliasso et al. (2014)

Origliasso *et al.* (2014) investigated uniaxial compressive strength, Cerchar abrasivity index and machine-rated power as critical factors to evaluate the machine productivity of SM, which was expressed as Equation 2.27.

$$\mathrm{PR} = (2\mathrm{P_W} - 600)e^{-0.024[\sigma_c + 10(\mathrm{CAI}-0.5)]} \qquad \text{(Equation 2.27)}$$

where, PR represents the production rate (m3/h), P_W denotes the machine power (kW), σ_c signifies the uniaxial compressive strength (MPa), and CAI is the Cerchar abrasivity Index.

k) Prakash et al. (2015)

Prakash *et al.* (2015) investigated the key performance indicators of SM, namely, production, diesel consumption and pick consumption in coal and limestone mines. The rock cuttability index (RCI_{SM}) was established based on machine, rock mass, and intact rock factors. The relations of actual production, diesel and pick consumptions per 1000 t with RCI_{SM} are expressed as follows:

$$\mathrm{RCI_{SM}} = \frac{1000\mathrm{MF}}{\mathrm{RMF}\times\mathrm{IRF}} \qquad \text{(Equation 2.28)}$$

$$\mathrm{RMF} = \frac{\mathrm{IV_p}}{\mathrm{RN}} \qquad \text{(Equation 2.29)}$$

$$\mathrm{IRF} = \mathrm{E} \times \mathrm{CAI} \times \mathrm{LV_p} \qquad \text{(Equation 2.30)}$$

$$\mathrm{MF} = \frac{\mathrm{EP}\times\mathrm{CS}\times\mathrm{CA}}{1000} \qquad \text{(Equation 2.31)}$$

$$\mathrm{TPH} = 181.5\mathrm{RCI_{SM}^{0.245}} \quad (R^2 = 0.85) \qquad \text{(Equation 2.32)}$$

$$\mathrm{DCT} = 338\mathrm{RCI_{SM}^{-0.19}} \quad (R^2 = 0.89) \qquad \text{(Equation 2.33)}$$

$$\mathrm{PCT} = 2\mathrm{RCI_{SM}^{-0.18}} \quad (R^2 = 0.79) \qquad \text{(Equation 2.34)}$$

where, RCI_{SM} signifies the rock cuttability index for surface miner, RMF represents the rock mass factor, IRF represents the intact rock factor, MF represents the machine parameter, IV_p states the insitu P-wave velocity (m/s), RN states the rebound hardness number, E states the Young's modulus (GPa), CAI states the Cerchar abrasivity index, LV_p states the laboratory P-wave velocity (m/s), EP states the engine power (kW), CS states the cutting speed (m/min), CA states the cutting area (m^2), TPH states the production (t/h), and DCT and PCT signify diesel and pick consumptions, respectively.

l) CMPDI model

Wirtgen GmbH (2008) evaluated the rated productivity of SM as a product of its cutting width, cutting depth, and average cutting speed of the machine. According to the code for uniform system of maintenance, control and verification of coal stock, CIL, the total coal tonnage produced is determined by the product of average density of a coal seam and the rated productivity of machine. However, according to the Central Mine Planning and Design Institute Limited (CMPDI), machine productivity depends on the ratio of its utilisation to availability percentage of the machine after considering the effect of machine's ancillary times during coal cutting in opencast mines. Equation 2.35 denotes the CMPDI model to assess the machine productivity of SM in opencast coal mines.

$$A_M = \frac{W \times D \times V \times \gamma \times U \times 60}{A} \quad \text{(Equation 2.35)}$$

where, A_M signifies the machine productivity (t/h), W depicts the cutting width (m), D depicts the cutting depth (m), V depicts the cutting speed (m/min), γ depicts the in-situ density of coal (t/m^3), U depicts the machine utilisation (%), and A depicts the machine availability (%).

2.5.2 Summary of machine productivity models

Table 2.8 describes machine productivity models for SM along with the name of authors, year, study domain, key features and limitations to understand their scope of application, allowing for necessary modifications based on a mechanical excavation system.

Table 2.8: Summary of machine productivity models for SM

Author, Year	Productivity model equation	Study domain with key features and limitations
Jones and Kramadibrata, 1995	$PR = 1005 - (559 \times \ln\sigma_c)$	♦ A logarithmic relationship was established between production rate and UCS based on experimental data. ♦ Production rate decreases with increasing UCS. **Limitations:** ♦ This model considered only the UCS, i.e., up to 60 MPa.
Kramadibrata and Shimada, 1996	$L = \left(\frac{N}{RCI\sigma_c}\right)$	♦ The rock cuttability index (RCI) of surface miner was developed by considering rated power, specific weight, discontinuity spacing, Young's modulus, abrasivity and tensile strength as functional parameters. **Limitations:** ♦ Machine and operational parameters were not considered.
Murthy *et al.*, 2009	$NTPH = b_0(CISM)^{b_1}$	♦ A cuttability index was proposed to evaluate the production performance of SM in coal and limestone mines, by integrating machine specifications and pysico-mechanical properties of rock. ♦ Engine rated power, cutting speed and cutting area were considered as machine factor. ♦ P-wave velocity in field as well as in laboratory and percentage of silica were considered. **Limitations:** ♦ Variation in predicted performance needs attention. ♦ Operational factors present in mines were not considered.
Dey and Ghose, 2011	$L = \left(1 - \frac{CI}{100}\right) kM_c$	♦ A cuttability index (CI) was established using rock mass properties and machine power. ♦ The prediction model extends Gehring's formula in which coal and limestone mines are covered. **Limitations:** ♦ Technical specifications and design of machine along with the operational factors related to mines were not considered.
Origliasso *et al.,* 2014	$PR =$ $(2P_W - 600)e^{-0.024[\sigma_c + 10(CAI-0.5)]}$	♦ The production rate of SM was estimated based on machine power, uniaxial compressive strength (UCS) and Cerchar abrasivity index. **Limitations:** ♦ Error in predicting production rate was observed as 25%.
Prakash *et al.*, 2015	$TPH = 181.5RCI_{SM}^{0.245}$ $DCT = 338RCI_{SM}^{-0.19}$ $PCT = 2RCI_{SM}^{-0.18}$	♦ The rock cuttability index (RCI) was established based on intact and rock mass parameters along with machine parameter. **Limitations:** ♦ These models can be fine-tuned considering more type of rocks and associated operational parameter present in mines.

2.5.3 Identification of factors influencing machine productivity

Table 2.9 shows a total of fourteen distinct factors related to rock properties, technical specifications of machine and operational strategies are considered to understand their relevance in evaluating key productivity indicators of continuous excavation machines. Seven factors, namely, uniaxial compressive strength, tensile strength, ash content, moisture content, machine power, machine specifications and operation strategy were identified as factor influencing machine productivity based on their occurrence frequency in studied productivity models.

Table 2.9: Factors used in different models to evaluate machine productivity

S. N.	**Model↓ / Parameter→**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
1	Farmer (1986)	■								■			■	■	
2	Roxborough (1987)	■					■								
3	Bilgin *et al*. (1988 and 1997a,b)	■											■		
4	Gehring (1992)	■						■					■	■	■
5	Spero (1990)				■	■	■								
6	Jones and Kramadibrata (1995)	■													
7	Kramadibrata and Shimada (1996)	■	■	■						■			■		
8	Thuro (1997)		■											■	
9	Kahraman *et al.* (2003)	■	■	■							■				
10	Foster *et al*. (2004)				■		■								
11	Wigley and Williams (2005)				■										■
12	Bhatt (2006)				■										■
13	Murthy *et al.* (2009)		■			■			■				■	■	■
14	Mammen *et al.* (2009)	■					■								
15	Dey and Ghose (2011)							■			■	■	■	■	■
16	Origliasso *et al.* (2014)	■										■	■		
17	Prakash *et al.* (2015)								■	■		■	■	■	
18	CMPDI model			■										■	■
	Total	9	4	3	4	2	4	2	2	3	2	3	8	7	6

Legend notes: **1** is the uniaxial compressive strength, **2** is the tensile strength, **3** is the density, **4** is the ash content, **5** is the silica content, **6** is the moisture content, **7** is joints, **8** is the seismic velocity, **9** is the modulus of elasticity, **10** is the point load index, **11** is the Cerchar abrasivity index, **12** is the machine power, **13** is the machine specifications, **14** is the operation strategy.

2.6 Factors influencing key productivity indicators of surface miner

Machine productivity, pick consumption, and diesel consumption are identified as key productivity indicators of SM in opencast coal mines (Singh *et al.*, 2023c). Machine productivity is a function not solely of the coal itself but also the mechanism acting on it (Rzhevsky and Novik, 1971). It can be better judged by utilising a combination of coal, machine, and operational parameters present in an opencast coal mine, as illustrated in Figure 2.16. All these parameters were not covered together in the earlier models. Among these parameters, coal is a natural component of the earth's crust, making it an immutable parameter. However, machine and operational parameters are the product of human ingenuity and can be customised to meet specific requirements (Eskikaya and Tuncdemir, 2007). These parameters are detailed as follows:

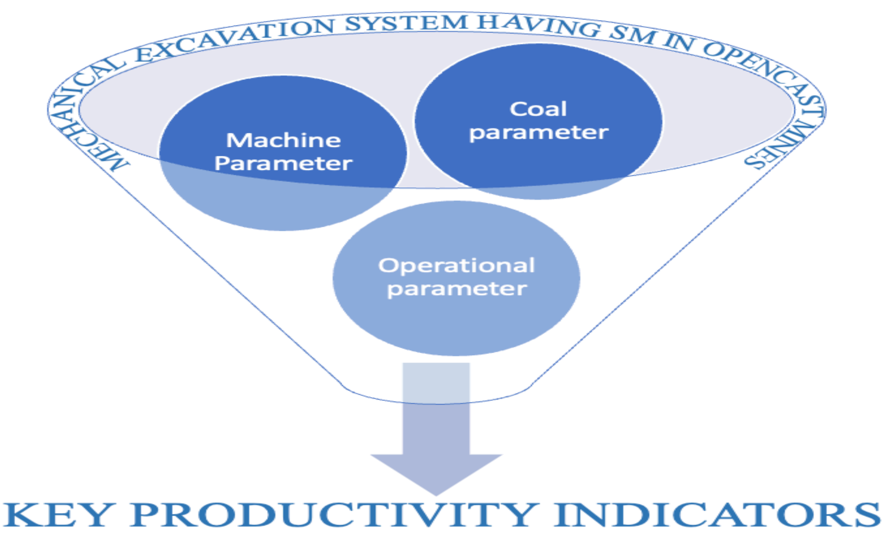


Figure 2.16: Parameters affecting productivity of SM in opencast coal mines

2.6.1 Factors related to coal parameter

Based on the literature review, uniaxial compressive strength, tensile strength, ash content, and moisture content were identified as factors related to coal parameter influencing key productivity indicators of SM in opencast coal mines. These are explained as follows:

a) Uniaxial compressive strength

The most utilised factor of strength, deformation, and cuttability of rocks is observed as the uniaxial compressive strength (UCS) (Erosy and Waller, 1995; Atilla *et al.*, 2004). Barendsen (1970) proposed a relationship between machine productivity and UCS for the tunnelling machines working on the cutting (drag bit) and crushing (rotary bit) principles, respectively. SM manufacturers follow simple conjecture and use UCS of coal as the only yardstick to evaluate the cutting performance of their machines. Wirtgen (2008) suggested that UCS of rock mass affects machine productivity of SM. Figure 2.17 shows the effect of UCS on the rated productivity of SM, which goes down substantially with an increase in UCS. Murthy *et al.* (2009) reported a significant decrement in the machine productivity of SM due to an increase in UCS, *i.e.*, from 1050 t/h at 10 MPa to 100 t/h at 100 MPa of UCS at Cloud Break iron ore mine, Pilbara, Australia.

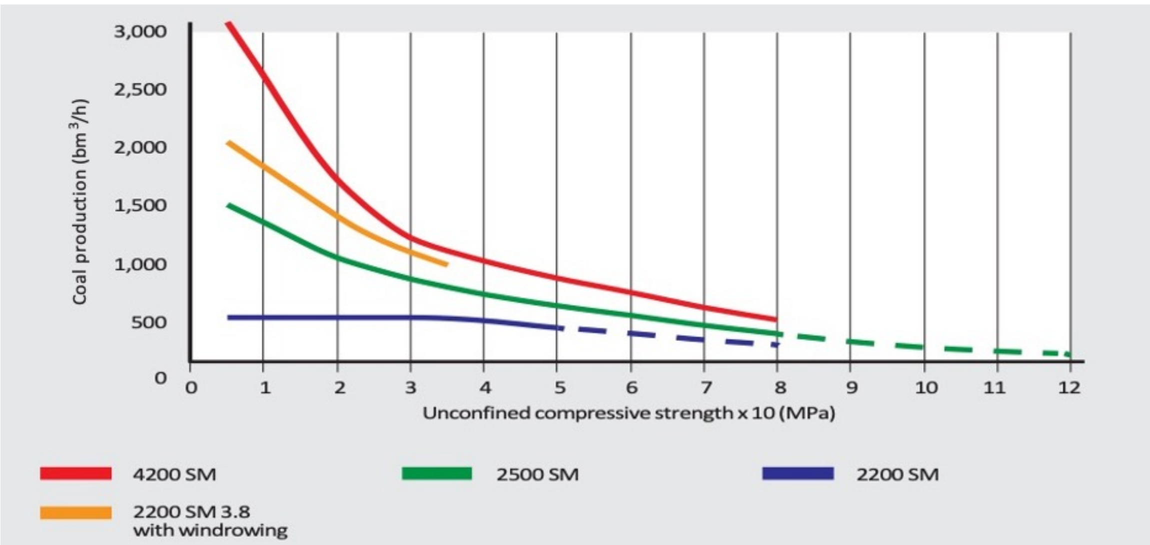


Figure 2.17: Effect of uniaxial compressive strength on SM productivity (Wirtgen, 2008)

b) Tensile strength

Tensile strength is used as a crucial factor in assessing rock strength (Prikryl, 2001). Famer and Glossop (1980) modified Graham's formula for average cutting force by substituting uniaxial compressive strength with tensile strength to evaluate the penetration rate of tunnel boring machines (mm/rev). Thuro (1997) and Kahraman *et al.* (2003) proposed the penetration rate of percussive drills based on the tensile strength of rock. Murthy *et al.* (2008) also observed tensile strength as a crucial factor while investigating the cuttability assessment of roadheaders. It is also used as a crucial factor to assess the cutting rate and bead wear rate of diamond wire saw (Jain and Rathore, 2010).

c) Ash content

Conventionally, the amount of ash in non-coking coal defines its quality (Bolortuya *et al.*, 2013; Cheepurupalli *et al.*, 2015; Singh *et al.*, 2023e). Table 2.10 details the delineation of coal seam according to the Indian standard norms applicable to non-coking coal. SM cuts coal, shaly coal and carbonaceous shale and avoids dirt bands more than 1 m in thickness consisting of grey shale, sandy shale and sandstone in opencast coal mines.

Table 2.10: Categorisation of coal seams in Indian opencast mines

S.N.	Coal seam particular	Low moisture coal	High moisture coal
1	Coal	Ash% up to 35%	Ash% + Moisture% up to 40%
2	Shaly coal	Ash% > 35% up to 50%	Ash% + Moisture% > 40% up to 55%
3	Carbonaceous shale	Ash% > 50% up to 70%	Ash% + Moisture% > 55% up to 75%
4	Dirt bands (Grey shale, sandy shale and sandstone)	Ash% exceeding 70%	Ash% + Moisture% exceeding 75%

Ash content in coal affects the flow hydrodynamics of unprocessed coal, and coal with higher ash content exhibited higher friction force (Nair *et al.*, 1990). Terchick *et al.* (1963) and Meintjes (1965) proposed the ash content as a one quantity that is portrait to induce abrasiveness in coal. More ash in coal means higher abrasive wear, resulting into frequent tool assembly replacements vis-à-vis productivity loss for coal milling machines in a mechanical excavation system (Foster *et al.*, 2004). Wigley and Williams (2005) reported that the coals that are free of ash would not cause significant abrasion wear in full scale machine during coal comminution. Bhatt (2006) studied the effects of variation of ash in coal from 6% (taken as standard) up to 75% (extreme) on component performance and observed that drum mills show an increase in component consumption of 115% in ball-race mills and 30% in bowl mills based on experimental data.

d) Moisture content

Moisture content affects the uniaxial compressive strength of rock (Fowell *et al.*, 1986). Mammen *et al.* (2009) has examined the impact of moisture content on rock cutting performance parameters related to roadheaders. A saturated sandstone sample exhibited a 68% decrease in uniaxial compressive strength compared to that of a dry sample. The cutting force was reduced by 40%, specific energy by 38%, and impact wear of the cutting tool by 80% during saturated sandstone sample cutting. However, the cutting of some saturated rocks becomes difficult due to the dissipation of high-stress concentration at the pick-rock interface from pore water. The cutting of a rock mass with high moisture content resulted in a lower bit consumption (Roxborough, 1987). Spero (1990) studied the abrasion phenomena in a mill fitted to the actual boiler and proposed that the moisture is the critical constituent of coal which affects component consumption in a full-scale comminution process of coal.

2.6.2 Factors related to machine parameter

Design configurations and technical specifications of machine define its productivity in a production process (Murphy and Daneshmend, 2006). Cutting tool configuration and technical specifications of SM are crucial to determine machine productivity in opencast mines (Prakash *et al.*, 2012). Factors related to cutting tool configuration, namely, pick type, number of picks, tip angle and attack angle were considered as fixed factors for different models of SM, whereas, factors related to technical specifications, namely, rated engine power (Dey and Ghosh, 2011; Origliasso *et al.*, 2014), cutting drum width (Wirtgen, 2008; Kramadibrata *et al.*, 2015), cutting drum depth (Wirtgen, 2008; Kramadibrata *et al.*, 2015), cutting area (Prakash *et al.*, 2015), and cutting speed (Wirtgen, 2008; Kramadibrata *et al.*, 2015) were taken as variable factors to predict key productivity indicators of SM.

2.6.3 Factors related to operational parameter

Operational strategies in accordance to work site conditions can improve machine productivity by minimising several reasons leading to the changes in ancillary times for a machine in opencast coal mines (Rai *et al.*, 2011; Rai *et al.*, 2020). For example, regular maintenance tasks, such as machine cleaning, oil changes in the engine and gearbox, coolants for the radiator, pick replacements, water refilling, and air/oil filter servicing are necessary to lower down the number of SM breakdowns.

Operational parameter depends on how SM operation strategies are effectively utilised for its conversion into cutting time. Machine availability with due consideration of maintenance and breakdown times and machine utilisation including consideration for case specific ancillary times like manoeuvring and operationally necessary ancillary times like changing trucks, limits the machine productivity in opencast coal mines (Raghavan *et al.*, 2021; MOC, 2022). It refers to the ratio of available shift time to scheduled shift time of SM for coal mining in an opencast mine, as shown in Equation 2.36. The extent to which the productive capacity of SM is used during its total available time is defined as its utilisation. The machine utilisation refers to the ratio of actual cutting time to scheduled shift time of SM for coal production in an opencast mine, as described in Equation 2.37.

A = (SST – MT – BT) / (SST) (Equation 2.36)

U = (SST – IT – MT – BT) / (SST) (Equation 2.37)

where, A is the SM availability, U is the SM utilisation, SST is the scheduled shift time (h), BT is the breakdown time (h), MT is the maintenance time (h), IT is the idle time (h).

Cutting time for SM increases significantly with increased face length worked by SM in opencast coal mines, therefore, extent to which machine productivity of SM is influenced by ancillary times depends on the working face length (Wirtgen, 2008). Figure 2.18 illustrates the cutting time percentage as a function of the length worked for SM cutting hard and soft rocks in combination with the different loading modes affecting machine productivity of SM in opencast coal mines (Wirtgen, 2008). Figure 2.19 details the list of factors related to coal, machine and operational parameters, affecting key productivity indicators of SM in opencast coal mines.

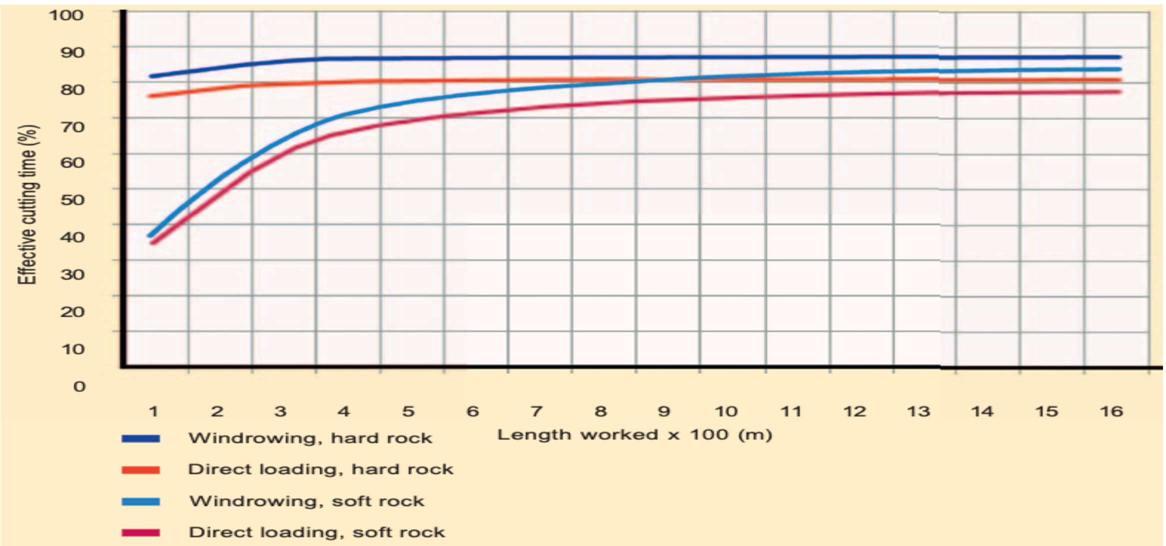


Figure 2.18: Effective cutting time as a function of face length (Wirtgen, 2008)

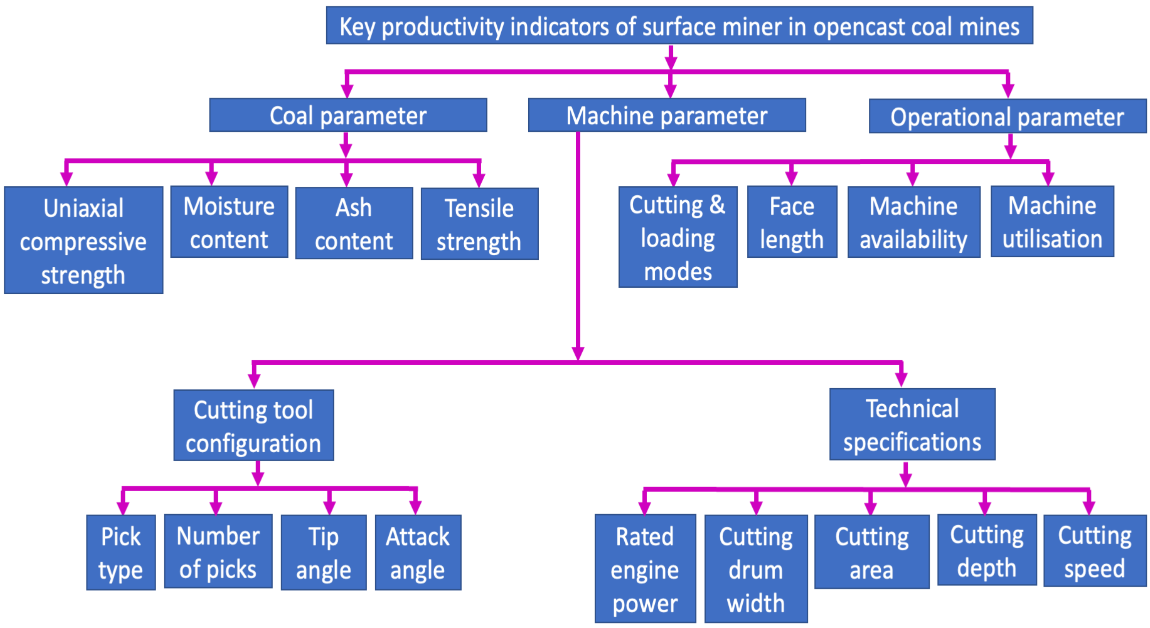


Figure 2.19: Factors affecting key productivity indicators of SM in opencast mines

2.7 Total factor productivity

According to the neoclassical model in economics, there have been number of efforts over the years to define and quantify productivity and identify the relationship between the production factors. These mostly concentrated on developing a single factor productivity index, such as, machine productivity, to focus on the reasons for the downturns rather than examining the factors that cause productivity growth. It has also been pointed out that machine productivity in terms of output per hour may be incorrectly interpreted as a solely changes in the cutting time of machine, as there are many other vital factors to consider, such as, changes in capital input, cost/cutting time ratio, technology.

Szwilski (1988) argue that a useful approach for evaluating output per hour in a coal mine would be to assume that coal production is an economic production process, where production factors are converted into an output, as shown in Figure 2.20. Under this assumption, output per hour estimation problem becomes the problem of understanding the relationship between production factors and outputs. Once the total factor productivity is measured, managers can change production factors to maximise the production output.

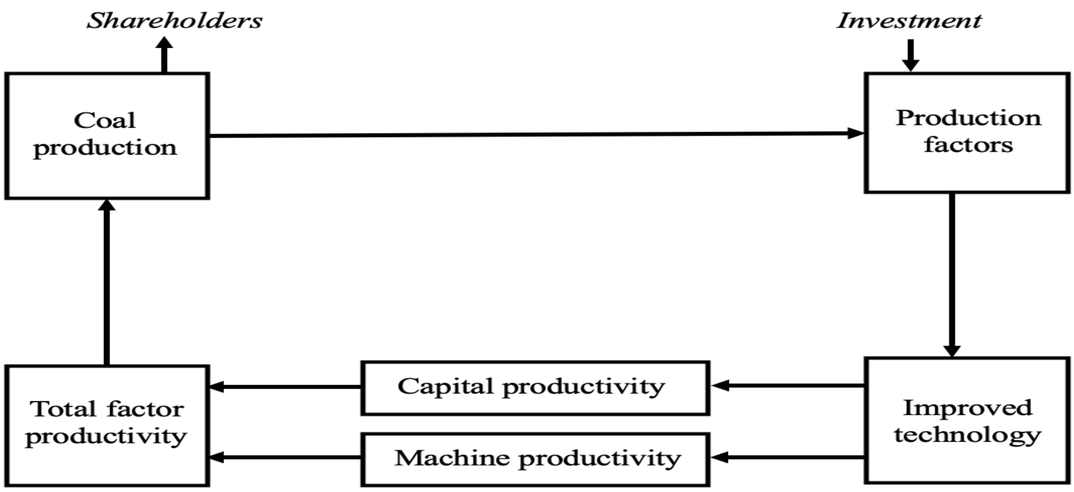


Figure 2.20: Importance of total factor productivity in coal production process

Economic theory describes the production function as a technical relationship between the output and production factors, namely, machine, capital and technology (Philip Wicksteed 1894; Cheng and Han, 2017). In alignment with the traditional neoclassical economics, this study excludes 'energy' as a production factor due to its perception as an intermediate product. Equation 2.38 describes the production function between output and production factors.

$$Q \propto f(M, K, A) \qquad \text{(Equation 2.38)}$$

where, Q is the coal production (t), M is the machine (h), K is the capital (₹), and A is the technology coefficient or total factor productivity.

In the literature, various forms of production functions exist mathematically. These include constant elasticity substitution production function, linear production function, Cobb-Douglas production function, Leontief production function, variable elasticity of substitution and translog production function (Cheng and Han, 2017). Some researchers employed non-parametric data envelopment analysis (DEA) to ascertain relationships of economies or diseconomies of scale in production process, yet the findings of their investigations remained inconclusive (Banker *et al.*, 1994; Kulshekhra and Parikh, 2002

Banker; and Natarajan, 2008). Different conclusions are drawn on the economic relationship of production factors using the same data due to its unsuitable assumptions for evaluating the total factor productivity of technology (Kitchenham, 2002).

2.7.1 Total factor productivity models – a review

The absolute values of productivity depend on the measurement technique utilised and the way inputs are measured. Several production functions based on the multiple production factors have been developed by different researchers to offer a framework for empirical and theoretical analysis based on role of production factors in evaluating total factor productivity or technology coefficient (Szwilski, 1988; Ghobadian and husband, 1990; Kulshreshtha and Parikh, 2002; Agbenyegah, 2007; Pendharkar *et al.*, 2008; Shen *et al.*, 2013; Costa *et al.*, 2014; Wang, 2020; Başeğmez, 2021; Sharf and Mikhalchuk, 2021). Table 2.11 details the total factor productivity models at macroeconomic level along with the name of authors, year, study domain, production model and purpose to understand their scope of application, allowing for necessary modifications based on the production process.

Table 2.11: Summary of total factor productivity models

Author/Year	**Study domain**	**Production function/Model**	**Output variables**	**Production factor / Input**	**Purpose of the model**
Szwilski, 1988	Coal mines	Cobb-Douglas; TFP = Q/(aL+bK)	Coal production (tons)	labour-hours and capital investments	♦ Measurement of Total factor productivity.
Ghobadian and husband, 1990	Company in England	Frontier approach, Cobb-Douglas; $P = 4.046K^{0.296}L^{0.682}$	Net value of output	labour-hours, capital investments	♦ Measurement of absolute values of productivity to assess the technical progress.
Pendharkar *et al.*, 2008	Software development effort	Cobb-Douglas; $Cost = 17.41 \times (Software)^{0.623} \times (Team)^{0.770}$	Software cost	Team size, software size	♦ Whether software development effort exhibits Cobb–Douglas functional form with respect to team size and software size.

Kulshreshtha and Parikh, 2002	Opencast and underground coal mining in India	Data envelopment analysis; $\theta^t = \{D^t(x^t y^t)\}^{-1}$, $m_i(y_s, x_s, y_t, x_t) = \frac{d_i^t(y_t,x_t)}{d_i^s(y_s,x_s)}\left[\frac{d_i^s(y_t,x_t)}{d_i^t(y_t,x_t)} \times \frac{d_i^s(y_s,x_s)}{d_i^t(y_s,x_s)}\right]^{\frac{1}{2}}$, effch $= \frac{d_i^t(y_t,x_t)}{d_i^s(y_s,x_s)}$, techch $= \left[\frac{d_i^s(y_t,x_t)}{d_i^t(y_t,x_t)} \times \frac{d_i^s(y_s,x_s)}{d_i^t(y_s,x_s)}\right]^{\frac{1}{2}}$, tfpch = effch×techch	Coal production (‘000 tonnes) and overburden removal (‘000 cubic meters)	Mining machineries (horse power unit) and labour (manshift)	♦ Comparison of change in total factor productivity of opencast and underground mines between two data points based on changes in labour productivity and geometric mean of the shift in technology from period s to t.
Agbenyegah, 2007	Economic sectors in Australia	Cobb-Douglas; $Y_t = 48.89 \times K^{0.199} \times L^{0.464} \times H^{0.084} \times FDI^{0.075} \times ICT^{0.162}$	Gross Domestic Product	Fixed capital, labour units, human capital, foreign direct investment, information and communication technology	♦ Level of technology as a measure of total factor productivity in a production function accounted for the influences of production factors vis-à-vis technical progress in sectors.
Shen *et al.*, 2013	construction time-cost	Cobb-Douglas; Scenario: constant return to scale with $\alpha = 0.3$, $\beta = 0.7$ and $A = 1$	Production rate	Capital per unit of effective labour	♦ Development of framework using CDPF to solve construction time-cost trade-off problem.
Costa *et al.*, 2014	Power distribution utilities in Brazil.	Data envelopment analysis, Cobb-Douglas; $X_j = \beta_0 \times Y_{1j}^{\beta_1} \times Y_{2j}^{\beta_2} \times Y_{3j}^{\beta_3} \times (Y_{3j}Y_{2j})^{\beta_4}$	Operational Cost (R$)	Network length (km), Number of customers, Weighted power consumption (MWh)	♦ Whether operational cost exhibits Cobb–Douglas functional form with respect to the combination of production factors.

Wang, 2020	Countries around the globe	Cobb-Douglas and translog; Scenario I: $(\beta_1 = 0.25, \beta_2 = 0.25, \beta_3 = 0.25, \beta_4 = 0.25)$. Scenario II: $(\beta_1 = 0.4, \beta_2 = 0.3, \beta_3 = 0.2, \beta_4 = 0.1)$. Scenario III: $(\beta_1 = 0.3, \beta_2 = 0.25, \beta_3 = 0.15, \beta_4 = 0.1)$. Scenario IV: $(\beta_1 = 0.3, \beta_2 = 0.3, \beta_3 = 0.3, \beta_4 = 0.3)$.	Life expectancy at birth, Combined gross enrolment ratio for primary, secondary, and tertiary schools, Gross domestic product per capita	Basic requirements, efficiency enhancers, innovation and sophistication factors	♦ Simulations based on Cobb-Douglas and translog production functions with both single output and multiple outputs were observed to obtain the true productivity values vis-à-vis the true rankings which serve as the benchmark to compare all ranking methods.
Başeğmez, 2021	Developing countries around the globe	Cobb-Douglas; $GDP = 11.001 \times K^{0.602} \times L^{0.455} \times E^{0.147}$	Gross Domestic Product (million $)	Labour, Capital, Quad btu energy consumption	♦ To study short-term and medium-term effects of energy on economic growth.
Sharf and Mikhalchuk, 2021	Oil and gas industry in Russia	Data envelopment analysis and Cobb-Douglas; $A_{UR} = 3.171$, $A_{KR} = 2.35$, $A_{TO} = 1.857$, $A_{RT} = 1.3$, $A_{SO} = 0.87$	Gross regional product per capita,	Oil recovery and oil reserve addition	♦ Assessment of weight share of production factors and technology coefficients for five constituent RF regions, investigating interregional resource imbalance.

2.7.2 Production functions to measure total factor productivity

Nevertheless, in recent years a lot of efforts have been put to define and quantify the productivity in coal mines and identify the relationship between the constituent elements of the total factor productivity. These efforts mostly concentrated on developing partial labour productivity and machine utilisation indices. Labour productivity, gauged in output per man shift, is most commonly used in the coal mining industry as a measure of changes in labour efficiency of the coal production process. Equation 2.39 shows a bivariate exponential production function (BEPF), limited to the single production factor, *i.e.*, ‘labour’ input, to develop a coal production model.

$$\mathrm{Y} = \mathrm{A}(\mathrm{L})^{\alpha} \qquad \text{(Equation 2.39)}$$

where Y is the total production, representing the value of all goods produced, L is the labour input, α is the output elasticity to labour, A is a productivity parameter.

After applying logarithms to both sides, a production function is solved using linear regression to measure a productivity parameter, as shown in Equation 2.40.

$$\ln(\mathrm{Y_{it}}) = \beta_0 + \alpha \ln(\mathrm{L_{it}}) + u_{it} \qquad \text{(Equation 2.40)}$$

where β_0 is a parameter and u_{it} is the error term.

This exponential function relationship isn’t novel and was initially suggested in the late 1970s (Walston and Felix, 1977). However, according to Banker and Slaughter (1997), this model fails to accommodate the potential for increasing returns in specific projects. Empirical models also suggested that managers frequently adjust ‘capital’ input to vary ‘returns to scale’ economies (Hu *et al.*, 1998; Kulshreshtha and Parikh, 2001; Pathak and Rodkar, 2011; Hassani 2012).

Cobb and Douglas (1928) proposed the production modelling based on empirical observations that could be linked to inputs, such as, labour, capital, and technology through a multivariate non-linear function for elucidating various production activities. Cobb-Douglas production function (CDPF) has found extensive application in measuring the economics of production (Meeusen and Broeck, 1977; Dennis *et al.*, 2010; Oryani *et al.*, 2021), technological progress (Kulshreshtha and Parikh, 2002; Agbenyegah, 2007; Sircar and Choi, 2009; Yuan *et al.*, 2009), and total factor productivity (Szwilski, 1988; Ghobadian and Husband, 1990; Pendharkar *et al.*, 2008). Equations 2.41 and 2.42 outline the typical structure of CDPF.

$$Y = f(L, K) \quad \text{(Equation 2.41)}$$

$$Y = AL^{\alpha}K^{\beta} \quad \text{(Equation 2.42)}$$

where, Y, α and L are explained previously, K is the capital input or overall capital investment on a fixed asset, A is a total factor productivity or technology constant, and β is the output elasticity to capital or sensitivity of a production process to the change in a level of 'capital' input.

The prevalent method for estimating production function parameters entails linear logarithmic transformation of Equation 2.42, as shown in Equations 2.43 and 2.44.

$$\ln(Y_{it}) = \beta_0 + \alpha \ln(L_{it}) + \beta \ln(K_{it}) + u_{it} \quad \text{(Equation 2.43)}$$

$$\beta_0 = \ln(A) \quad \text{(Equation 2.44)}$$

The CDPF possesses several appealing characteristics. It is a homogeneous function of degree (α + β), assuming that α and β are non-negative and statistically significant. It implies that multiplying inputs "labour" and "capital" by a factor k will result in a change in total production by the factor $k^{(\alpha+\beta)}$. The exponent coefficients signify the flexibility coefficient of each input factor's marginal productivity, delineating the contribution of each input factor to the achieved output level. Additionally, the summation of exponents denotes returns to scale.

- If (α + β) > 1, there is an increasing return to scale (IRS) relationship, where doubling labour and capital inputs yields more than double output.
- If (α + β) = 1, it indicates a constant return to scale (CRS) relationship, with double inputs producing double output.
- If (α + β) < 1, there is a decreasing return to scale (DRS) relationship, yielding less than double output with doubled inputs.

It also exhibits robustness in handling outliers in production engineering datasets (Pickard *et al.*, 1999). However, one limitation of CDPF is its requirement of two input factors, i.e., 'labour' and 'capital' inputs, to explain total production (Liao *et al.*, 2010).

Figure 2.21 depicts a set of isoquants for a production function using CDPF. An isoquant is a contour line that connects points where the same output quantity is produced while varying input quantities (Varian, 1992). For each output level, an isoquant is formed, depicting the rate at which labour input can be exchanged for capital input or vice versa, while maintaining output constant. Isoquants share similarities with indifference curves, i.e., they are convex to the origin, downward sloping, and do not intersect.

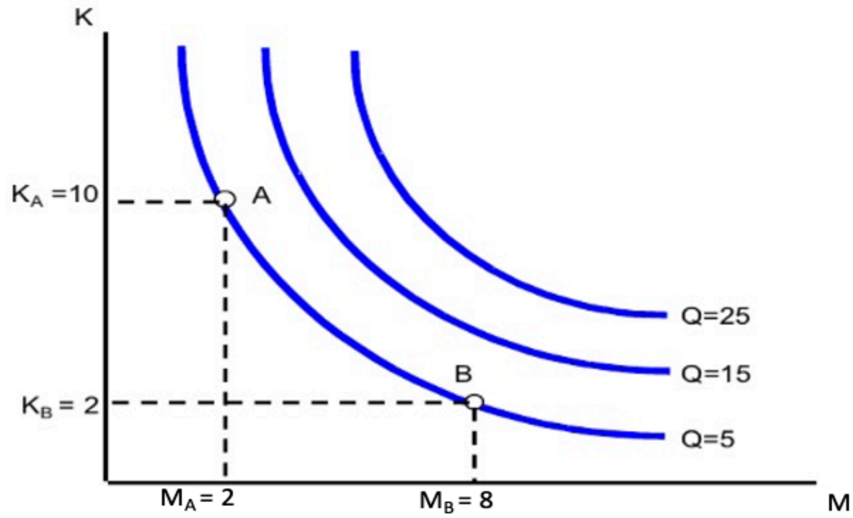


Figure 2.21: Illustrative isoquant curves from CDPF

2.7.3 Owning and operating costs of excavators

Capital is allocated for owning and operating mine machineries in opencast coal mines (Alba and Chicano, 2007). The effective management of total cost of owning and operating a machine govern the economic utilisation of 'capital' input into coal production. The economic analysis of any excavator in terms of its total ownership and operating costs (O&O) can be computed using Caterpillar method (Caterpillar, 2008), Corps of Engineers method (Atcheson, 1993; US Army, 2003), Association of General Contractors of America (AGC) method (Popescu, 1992), and Peurifoy method (Peurifoy *et al.*, 2006).

In case of SM particular to coal mining, none of these methods provide exact O&O costs of SM due to the numerous variables involved and the uncertain nature of mining. For example, machine repair, maintenance, and consensus generation in large machine shifts incur greater costs than in smaller shifts, which means that capital allocation tends to be higher for a large machine shift. But it doesn't inherently imply that small machine shifts are more cost-effective. In fact, research indicates that smaller shifts often lack problem-solving expertise compared to larger shifts, leading to biases in machine repair costs. Nonetheless, Finch and Fidler (1981), Schimm (1997), Aykul *et al.* (2007), Pathak and Rodkar (2011), and Nolan and Kecojevic (2014) have attempted to assess the O&O costs of SM using various modified approaches.

Except for the one-time initial capital cost of machine purchase, ownership cost is a fixed cost to incur annually, irrespective of machine usage. It comprises expenses related to depreciation, interest, taxes, and insurance on the initial capital cost. Conversely, operating cost is a variable cost to incur daily during machine usage. It comprises expenses related to maintenance and repair, fuel, consumable, manpower, special items and administrative overhead. The general guidelines for estimating excavator's O&O are described as follows:

a) Initial capital cost

The initial capital cost includes the factory price, additional equipment, sales tax, shipping, assembly, and erection. It accounts for approximately a quarter of the total investment over the machine's lifespan (Douglas, 1978). This expense covers preparing the excavator for operating in mines.

b) Depreciation cost

Machine experiences depreciation over time due to factors like age, deterioration, wear and tear, and technological advancements. It is calculated to zero value using straight-line method without considering taxes. However, this study includes the resale or salvage value of machine for tax incentives. The salvage value signifies the anticipated cash inflow from disposing of the machine at the end of its useful life. The useful life of an excavator is determined by its utilisation rate rather than the pace of technological advancements, rendering it obsolete and designated from the manufacturers' recommendations or the historical data of excavator. Meanwhile, straight-line depreciation method assumes that the machine is expected to depreciate at a uniform rate each year until it attains its salvage value. Equation 2.45 represents the straight-line depreciation cost for machines.

$$D_n = \frac{IC - SV}{n} \qquad \text{(Equation 2.45)}$$

where D_n represents the depreciation in year n (₹/yr), IC signifies the initial cost (₹), SV is the salvage value (₹), n represents the useful life (year).

c) Interest, taxes and insurance costs

Interest cost represents the annual capital expense invested in a machine (Nunnally, 1987). If a machine is purchased using borrowed funds, the machinery cost equates to the interest charged on these funds. Interest costs on borrowed money or capital investment can be accurately calculated by considering the time value of money using appropriate compound interest factors. However, an interest rate equivalent to the company's return on investment should be applied if the machine is acquired with company assets.

The tax cost of machine denotes the annual expenses of property taxes and licenses payable to the state or central government. While these costs are generally lower than depreciation and interest, they still warrant acknowledgement.

Insurance costs consist of the annual expenses for protecting machine against the risk of accidents, theft, fire, and natural disasters unrelated to user negligence for the owner. This cost depends on the initial capital cost and type and level of protection. Generally, rates for interest, taxes, and insurance rates for excavators vary between 3-9%, 2-5%, and 1-3% of the average annual investment, respectively (Lambie, 1980; Nunnally, 1987; Chandler, 2004). However, actual rates may vary depending on type and size of machine, place of purchase, and project location.

d) Average annual investment

The average annual investment (AAI) on an excavator was determined by averaging the cost at the beginning of the first year and the cost at the beginning of the last year of its useful life, as shown in Equations 2.46, 2.47 and 2.48.

$$AAI = \frac{IC+C_{n-1}}{2} \qquad \text{(Equation 2.46)}$$

$$C_{n-1} = IC - (n-1)D_n \qquad \text{(Equation 2.47)}$$

$$AAI = \frac{IC(n+1)+SV(n-1)}{2n} \qquad \text{(Equation 2.48)}$$

where, AAI is the average of annual investment (₹), IC signifies the initial cost related to SM (₹), C_{n-1} is the cost at the start of the final year of SM useful life (₹), n represents useful life (year), D_n signifies depreciation in year n (₹/yr), SV depicts salvage value (₹).

e) Repair and maintenance costs

Repair and maintenance costs exhibit characteristics of both fixed and variable expenses. Major repairs like engine overhauls or undercarriage unit replacements may be considered fixed costs if the owner anticipates and plans for these expenses in advance. However, minor repairs, such as preventive and routine maintenance of the machine are treated as variable costs to mitigate the impact of adverse site conditions on the machine. The annual repair and maintenance costs are categorised as routine maintenance cost and major breakdown repair and can be estimated using machine manuals.

f) Fuel cost

Fuel consumption occurs during the operation of an excavator. The hourly fuel cost is determined by multiplying the excavator's fuel consumption per hour by the unit price of fuel. The fuel consumption rate can be estimated using historical data.

g) Consumable cost

Consumables are the items required for the operation of an excavator that literally gets consumed during its operation. These include, but are not limited to lubricants, and other petroleum products. They also include filters, hoses, and strainers. These expenses are usually computed as percentage of the hourly fuel costs. The consumption data or the average cost factors for lubricating oil, grease, and filters for their excavators under average conditions are available from the excavator manufacturers.

h) Manpower cost

Usually, a unit of operator and helper is required for operating excavator. Their wages should include overtime, workmen's compensation insurance, security taxes, bonus, and fringe benefits in the hourly wage expense (Clough and Sears, 1994). Care must be taken by the companies that operate in more than one state or that work for central agencies, state agencies and private owners.

i) Special items cost

The cost of replacing high-wear items, such as, scraper blade, drilling bits, ripper tips, shanks, and shank protectors, should be calculated as a separate item of the operating cost. Usually, unit cost is divided by the expected life to yield cost per hour.

j) Administrative overhead cost

Administrative overhead cost is often overlooked because of the assumption that the previous job would have already paid for it. Regardless of these calculations, the costs of excavator mobilisation and demobilisation can be large and are always important items in any job where substantial amounts of excavators are used. These costs include freight charges (other than the initial purchase), unloading cost, assembly or erection cost (if required), highway permits, duties, and special freight cost (if any). These expenses are usually computed as percentage of the initial capital cost.

2.8 Summary of literature review

This study presents a comprehensive literature review on the cutting mechanism and evaluation of the cutting force during pick-coal interaction vis-à-vis energy productivity. It also highlights the effect of coal, machine and operational parameters on key productivity indicators of SM, namely, machine productivity, pick and diesel consumptions in opencast coal mines. From literature review, it may be summarised that the SM total factor productivity entails not only the effective utilisation of machine during coal cutting but equally important is the economic utilisation of 'capital' input, which is evaluated as the total owning and operating costs of machine. Towards this end, a host of studies have been reported in the estimation of total factor productivity at macroeconomic level. However, the following research gaps have been identified from the literature review.

2.8.1 Research gaps

a) In most of the research, the effect of coal properties and cutting geometry on the energy productivity has been discussed. However, optimisation of SM control factors to maximise energy productivity for varied tensile strength of coal requires to be investigated.

b) Most of the predictor variables for machine productivity models in proposed literature take into account only two attributes, namely coal and machine parameters in proposing an empirical relationship. Since, there are numerous factors related to operating conditions present at mining site that can influence the key productivity indicators of SM, hence, the operational parameter should also be considered for predicting the same.

c) From various literature studies, it has been observed that a lot of efforts have been put to define and quantify the productivity of a mining method and these efforts mostly concentrated on developing partial labour productivity and machine utilisation indices. Since, the coal production is an economic production process, where managers frequently adjust ownership and operating costs in case of mechanised coal mining to vary 'returns to scale' economies, hence, 'capital' input should be considered in conjunction with 'machine' input for the development of a production function to investigate total factor productivity of a mining method.

2.8.2 Novelty of research work

The novelty of the research has three key components:

a) Optimisation of SM control factors (cutting speed, cutting depth, and drum speed) to maximise energy productivity keeping in view the tensile strength of coal.

b) Prediction of key productivity indicators of SM in opencast coal mines based on coal, machine and operational parameters.

c) Development of a production function subject to 'cutting time' and 'capital' inputs for evaluating SM total factor productivity in opencast coal mines.