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Production scheduling of an iron deposit under ore grade uncertainty

Mineral deposits are associated with a lot of uncertainties like orebody continuity, grade of the ore and its quantity etc. Resource evaluation followed by the generating production schedule for exploitation under grade uncertainty is a challenging task which needs computer based algorithms for its computation. The present paper attempts to evaluate and create production schedule for an iron ore deposit in India using SURPAC mine planning software. The estimated hematite resource is 75 million tonnes (MT)having cut-off grade of 60% iron, 1% silica and 2% alumina. Out of 75 MT resources, the mineable reserve is 50 MT, which accounts for 66% of the total resource. Thereafter five yearly and monthly production schedules are generated for exploitation of the deposit. The annual rate of iron ore production by opencast mining method is estimated as 3.6 MT per annum for 13 years of mine life. For the purpose of scheduling, mining direction is preferred towards north because of its specific location since a significant amount of overburden can be dumped as backfilling.

Keywords: *Mine planning; Production scheduling; grade uncertainty.*

1. Introduction

India is one of the leading producer as well as exporter of iron ore in the world, with total available resources of over 28.52 billion tonnes of haematite and magnetite ore in the country (IBM, 2015). Increasing demand of iron ore leads to the quest for exploration of additional resources and their subsequent exploitation. Grade uncertainty, geotechnical complexity, and available ore resource of the deposit affect the mine planning and production scheduling. Therefore production plan constitutes these uncertainties along with operational parameters such as life of the mine and level of mechanization. As geotechnical complexity and uncertainty in grade increases, different scenarios are explored so that decision makers can execute the proposed plan of action. In the early stage of planning, the ore reserve is segregated, and the mine is disintegrated with short term and long-term plans for execution. These production schedules are aimed at completing unit mining operations in order to maximize the profit in a defined time-frame. In general, while a production plan expresses how to excavate the mineral, a schedule describes the time to perform the operation or group of operations. The extraction schedule is the excavation of the nested pits, in order from smallest to the largest pit (Boland et al., 2009). Therefore, in order to formulate the production scheduling of the mine, the material within the ultimate pit limits should be partitioned into smaller volumes – known as pushback – that can be developed using any of the pushback design algorithms, such as minimising stripping ratio within pushback (Elkington and Durham, 2011), maximising time value of money (Nanjari and Golosinski, 2013). Pushback allow the determination of the yearly production scheduling for the life of mine. Many manufacturing organizations generate and update production schedules, which are plans that state when certain controllable activities should take place (Herrmann, 2007). Moreover, production planning and scheduling in open pit mine is realized as a dynamic activity, hence it should be reviewed several times during the life of mine (Hamzenejady et al., 2006). Therefore production schedules should be flexible enough that can satisfy strategic mine planning according to dynamic requirements of the ore, operating conditions and techno-economic feasibility of the mineral deposit.

The economic viability of the project is greatly influenced by production scheduling. Hence, during early stage of planning, the feasibility of alternate mine design and production schedules should be explored and evaluated in order to reduce the overall mining cost and improve the overall economy in response to geological, geotechnical and mining uncertainties. The mine scheduling involving many uncertain parameters can be dealt with strategic plans that can be applied to get the optimum schedule with the application of computing technology. In order to exploit the ore deposit and maximizing the profit, several heuristic approaches have been applied for open pit mine planning and production scheduling, including mixed integer linear programming (Ramazan, 2006; Ramazan et al., 2005; Ramazan and Dimitrakopoulos, 2013); simulated annealing and genetic

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algorithms (Askari-Nasab et al., 2007), and branch and cut algorithm (Caccetta and Hill, 2003). Open pit mine design and production scheduling problem has been dealt with to find the most profitable mining sequence over the life of a mine (Godoy and Dimitrakopoulos, 2004). The risk associated with capital investment decisions to the grade uncertainty of the orebody can be integrated to project economics (Gershon, 1983), which can be reviewed during the life of the mine to maximize profit. Thus an efficient and executable production plan can substantially impact the profitability of the mining project. Back to 1965, Lerchs-Grossmann developed an algorithm for the ultimate pit limit that denotes the recoverable quantity of ore from the deposit (Lerchs and Grossmann, 1965).

Iron ore deposits in India are of sedimentary origin and the elements iron, silica, alumina and phosphorus are critical for ore quality. In the present paper, optimum production schedule is designed in order to exploit the hematite-rich iron deposit economically with specified ore tonnage and ore grade using Geovia Surpac software and Whittle software. Whittle software specifically deals with optimisation of economics of opencast mining projects (Whittle, 2006).

2. Estimation of haematite resource and pit optimization

For estimation of available hematite resource and delineation of optimum production schedules, an iron ore deposit of India has been considered. The process of orebody modelling and resource estimation used 71 borehole data and 2126 core samples of the deposit. The exploration borehole pattern was approximately 100m × 100m. Geological exploration of deposit leads to their geological modelling with estimation of resources and reserves of iron ore based on various criteria. For geological modelling and resource estimation, 13 borehole sections are prepared having section interval of 100 m. Thereafter the solid model of the deposit was generated and all 11 lithologies are then segregated into two distinct types, either representing the ore or waste. A block model containing more than 57% of iron and less than 5% of silica and alumina each is considered as ore in the resource model and rest is categorised as waste. The orebody model and mineral resource estimation were carried out in order to infer the quantity of the resource and quality of haematite ore in the deposit.

The critical geochemical parameters for evaluating the quality of iron ore are iron content (Fe%), silica content (SiO_2%), phosphorous content (P), alumina content (Al_2O_3%), and water and organic content measured as loss of ignition (Benndorf and Dimitrakopoulos, 2013); as they influence the physical and chemical properties of the product (e.g., steel and sponge iron) and the performance of the processing plant. However, this paper considers only three major geochemical parameters for grade estimation such as iron content (Fe%), silica content (SiO_2%) and alumina content (Al_2O_3%). Ore quality poses paramount importance as it affects the market price of the ore and viability of the project. Customers demand good quality iron ore as a raw material for their plant for further processing in making steel. In the present study, the cut-off grade of iron ore is presumed as 60% iron, restricting silica and alumina content to 1% and 2% respectively throughout the mine life. More silica and alumina content in iron ore can adversely affect the blast furnace productivity. The mineable reserves are then estimated by defining the ultimate pit limits for a set of economic parameters, using commonly the Lerchs and Grossmann algorithm for pit optimization (Lerchs and Grossmann, 1965). After estimation of the mineable reserves, the extraction schedules are generated to exploit the deposit. Any technological improvement of process plants/blast furnace to make suitable use of low grade ores can change the dynamics of ore reserve quantity and economy of the project and the project life.

Traditional approaches to mine planning optimization are based on a single estimation model of the orebody that is unable to account for in-situ variability and uncertainty associated with the description of the orebody (David, 1988). Based on drillhole data and their statistical properties, conditional simulations generate several equally probable models (or scenarios) of a deposit, each reproducing available data and information, statistics and spatial continuity, that is, the in-situ variability of the data. It cannot be eliminated that the block model selection process sometimes involves the experience, expertise and knowledge of the mine planner. The dimension of block size is 50 m×50 m in the North and East direction with height of 8m. A geological section of the hematite deposit is depicted in Fig.1. Quality control of the ore requires grade estimation of various radical values (e.g., iron, silica, and alumina) of the iron ore deposit that uses geo-statistical tools. However, in this paper, inverse-distance square method has been used to estimate radical values in the resource model. Thereafter the ore resource of the deposit is estimated as 75.2 million tonnes. The average grades of iron, silica and alumina in the estimated resource are 60.68%, 1.04% and 2.15% respectively. The distribution of the estimated iron ore values in the block model is depicted in Fig.2.

The Lerchs and Grossmann algorithm has been used to determine the ultimate pit, which generates several nested pits based on the economic and geotechnical parameters (Lerchs and Grossmann, 1965). Provision of the financial model for the mining project itself is a rigorous and complex issue, and its success completely depends on the reliability of choosing the resource model in the optimization stage. This process is iterative and complex and determines project viability and the cash flow sequence of the mining projects. Once the ultimate pit limits and various mining phases have been defined, it demands to set up the production schedule. Then the production schedule is executed to excavate the nested pits from the smallest to the largest pit. This process is called

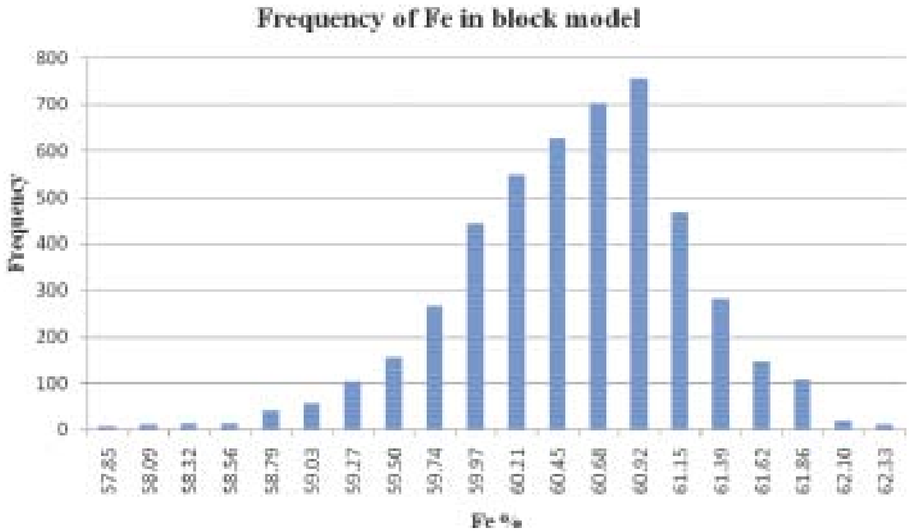

Fig.1 Geological sections of the deposit

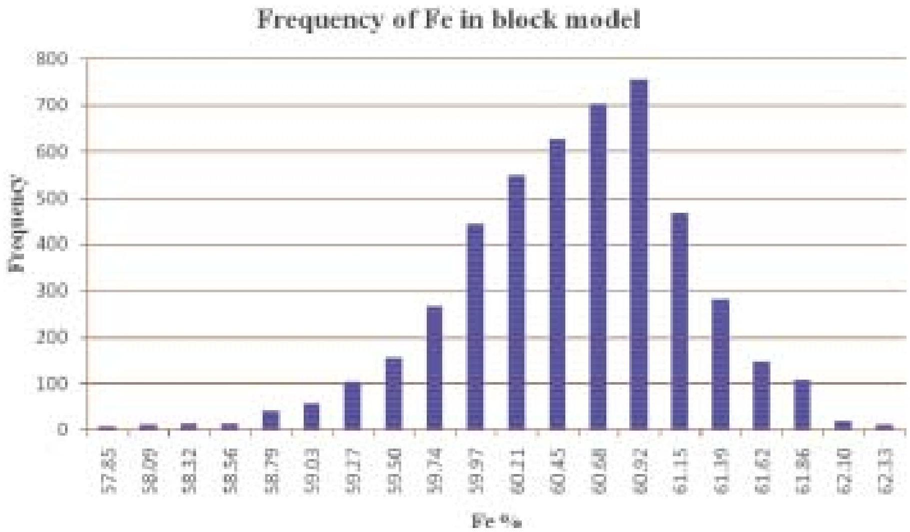

Fig.2 Descriptive statistics of the block model for the radical values of iron

pushback production scheduling, and it must follow the nested pits to synchronize the cash flow model during the optimization process.

Out of the estimated 75.2 MT of ore resource, 50.4 MT is delineated as mineable reserve for the designed ultimate pit limit with overall stripping ratio (mass of waste to mass of ore) of 0.544, simultaneously maintaining the average grade of iron, silica and alumina at 60.73%, 1.0% and 2.12% respectively. About nine million cubic meter of overburden will be removed to mine out these mineable reserves. Production scheduling of the deposit explains the time frame for completion of the mining activities to exploit the deposit for realising optimum profit out of the mineral deposit.

3. Production scheduling of the deposit

Production scheduling in opencast mines prioritizes the sequence of extraction of mineral blocks and waste blocks from the mine. Both the mineral blocks and overburden are subjected to a variety of physical and economic constraints. Typically, these constraints relate to the mining extraction sequence, processing plant capacities, quality of feed to the processing plant, stockpile-related restrictions, and various logistics issues. Rather than this, various operational requirements such as minimum mining width at pit bottom and maximum vertical depth do affect the extraction sequence and those requirements should be considered during planning stage. In this study, long-range production schedules denote a period of five years, which is further subdivided into short-term schedules consisting of annual and monthly schedules after following the push back schedule generated during the pit optimization process to observe the projected cash flow. The GeoviaMineSched has been utilized to generate various production scenarios.

Five production scenarios are generated through a combination of various constraints and parameters to attain an implementable and efficient production schedule. The long-term as well as short-term production schedules simultaneously reorganize the blending requirements at the pit. One of the production schedules that satisfies the operational feasibility and overall performance of the mining project has been chosen for pit design and production scheduling. The so designed initial production schedule should be flexible enough to meet the dynamic requirements of the ore, operating conditions and techno-economic parameters in future. Dynamic stockpile maintains a balance between the iron ore processing at the plant and mining capacity of the project and scope for blending the ore in the pit itself.

Production schedule in mines in general is designed to achieve a constant production rate with the desired quality at the process plant. Five distinct production scenarios (cases 1–5) are generated for different mining directions and combination of various parameters. From the Figs. 3 to 5, it can be stated that the ‘Case 2’ production scenario meets quality criteria for iron, silica and alumina, so it can be considered an optimum production schedule for the exploitation of haematite deposit. Among the available scenarios, mining direction towards the

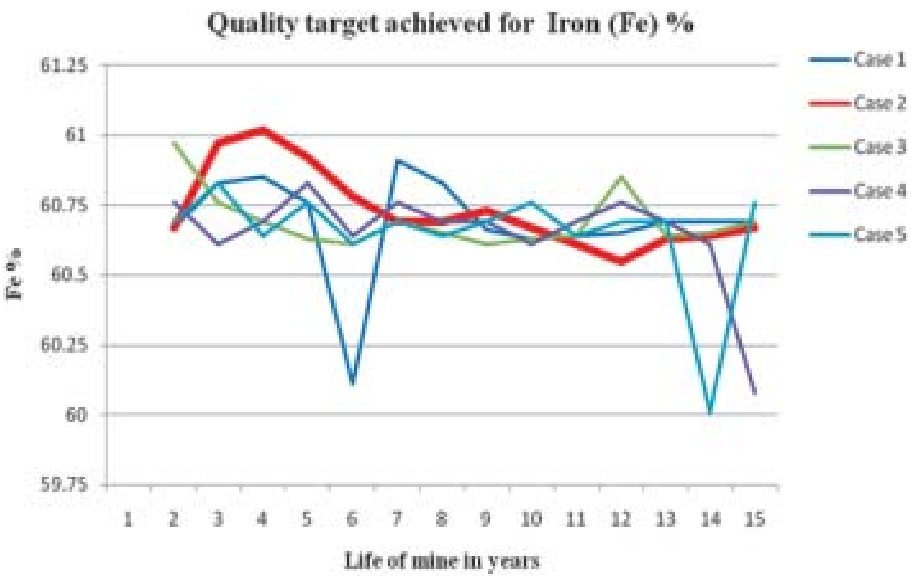

Fig.3 Quality target for Iron ore for the considered cases

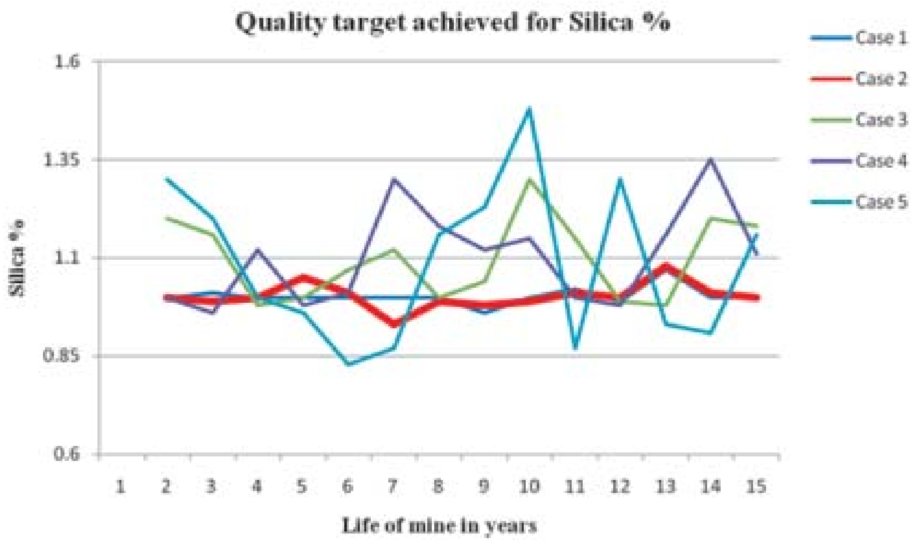

Fig.4 Quality target for silica for the considered scheduling scenarios

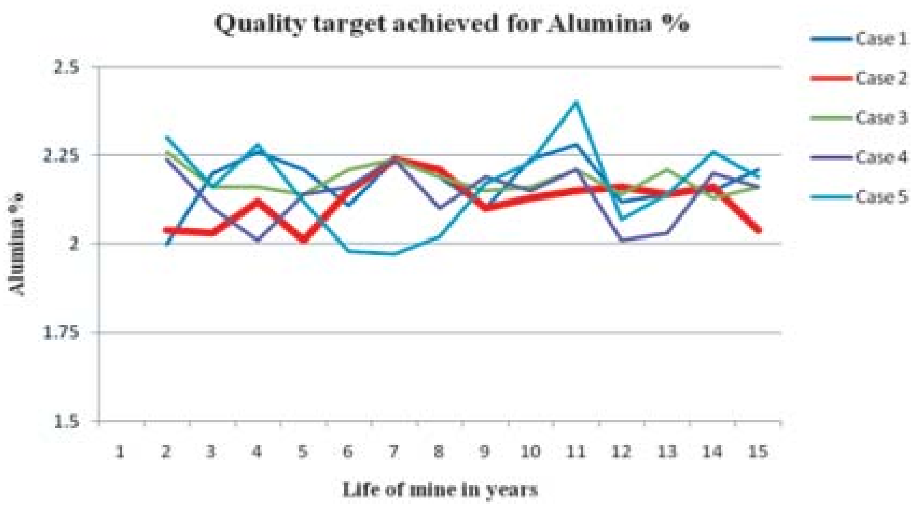

Fig.5 Quality target for alumina for the considered scheduling scenarios

north is preferred because it meets the specific quality targets and helps reducing the re-handling of the waste material as significant amount of overburden can be dumped into the internal dumps. As stated earlier, the production schedule is generated at a constant annual production of 3.6 MT iron ore with average grades of iron, silica and alumina at 60%, 1% and 2% respectively for 13 years of mine life. The mineable reserves accounts for 66% of the available resource. The achievable long-term production schedule has been presented in Table 1 and that of yearly production schedule is presented in Table 2. The short-term production schedule with monthly production target (Table 3) explains that the ore will be stocked in the stockpile after 11 months. Before that the iron ore processing plant is solely dependent on steady supply of iron ore from the mine for its uninterrupted operation. Figs.3 to 5 show the grades of iron ore available at ore processing plant, which can run for 14 years (mine life being proposed for 13 years) from the ore already stockpiled. This extra time of one year can be utilized for reclamation and rehabilitation of the open pit. The ore processing plant that is running longer than the pit excavation signifies the extended cash flow after the excavation operation. The quality target of iron ore in the optimum production schedule (case 2) is depicted in Figs.6 to 7.

4. Conclusion

Proper planning and production scheduling can increase the profitability of iron ore projects by minimising in-situ grade variability and uncertainty about the spatial distribution of ore. This study presents production scheduling of an iron ore deposit using geological data, whilst considering ore production, stripping ratios, and the generation of a detailed mining sequence from the previously determined mining rates, focusing on spatial evolution of mine production schedules. The block size of the resource model is 50m×50 m×8m. Out of

Table 1. Long-term (Five yearly) production plan for the iron ore deposit

Period Number (5 year)	Ore mined out from pit (MT)	Waste removed from pit (MT)	Ore balance of ore stockpile (MT)	Ore supplied to plant (MT)	Quality of ROM ore supplied to the processing plant		
					% Fe	% Si	% Al
1	18.881	12.419	0.621	18.260	60.83	0.99	2.05
2	21.196	10.104	3.557	18.260	60.64	1.00	2.18
3	10.274	4.858		13.831	60.72	1.03	2.17

Note: MT = Million tons; ROM = Run-of-mine

Table 2. Yearly production plan for ore and waste extraction from the mine

Period Number (year)	Ore removed from pit (MT)	Waste removed from Pit (MT)	Waste added to internal dump (MT)	Waste added to external dump (MT)	Stripping ratio (Mass of waste to ore)
1	2.970	3.290	1.646	1.644	1.108
2	3.830	2.430	1.213	1.217	0.634
3	3.810	2.450	1.226	1.223	0.643
4	3.896	2.364	1.183	1.181	0.607
5	4.164	2.096	1.049	1.048	0.503
6	4.356	1.904	0.952	0.952	0.437
7	4.771	1.509	0.754	0.755	0.316
8	4.430	1.810	0.907	0.903	0.408
9	4.621	1.639	0.820	0.820	0.355
10	3.687	2.573	1.286	1.287	0.698
11	4.018	2.262	1.131	1.131	0.563
12	3.892	2.368	1.183	1.185	0.608
13	1.905	0.688	0.343	0.344	0.361

Note: MT = Million tons

Table 3. Short-term production plan for first 24 months of the mine

Period number (Month)	Ore removed from pit (MT)	Waste removed from pit (MT)	Ore balance of ore stockpile (MT)	Ore added to plant (MT)	Fe (%)	Si (%)	Al (%)
1	0.308	0.202		0.308	60.46	1.01	2.00
2	0.201	0.270		0.201	60.58	1.00	1.99
3	0.233	0.267		0.233	60.61	1.00	1.99
4	0.264	0.256		0.264	60.56	0.98	2.00
5	0.197	0.323		0.197	60.59	1.00	2.00
6	0.216	0.294		0.216	60.78	1.00	2.00
7	0.204	0.336		0.204	60.73	1.00	2.00
8	0.201	0.309		0.201	60.69	1.00	2.00
9	0.256	0.241		0.256	60.75	1.00	1.99
10	0.264	0.226		0.264	60.77	1.00	2.00
11	0.257	0.243		0.257	60.78	1.00	2.16
12	0.369	0.171	0.059	0.310	60.95	1.00	2.06
13	0.379	0.141	0.127	0.310	60.94	0.98	2.03
14	0.321	0.150	0.196	0.300	61.05	1.00	2.00
15	0.235	0.285	0.217	0.310	60.97	1.00	2.00
16	0.311	0.200	0.142	0.300	60.87	1.01	2.00
17	0.265	0.240	0.153	0.310	61.02	1.00	2.01
18	0.291	0.213	0.108	0.300	60.86	1.00	2.11
19	0.272	0.228	0.099	0.310	60.86	0.99	2.09
20	0.401	0.139	0.061	0.300	60.85	0.99	2.03
21	0.406	0.071	0.162	0.300	60.95	0.99	2.05
22	0.374	0.086	0.268	0.310	60.97	0.99	2.08
23	0.302	0.178	0.332	0.300	60.95	0.90	2.06
24	0.273	0.237	0.334	0.310	61.02	0.94	2.04

Note: MT = Million tons

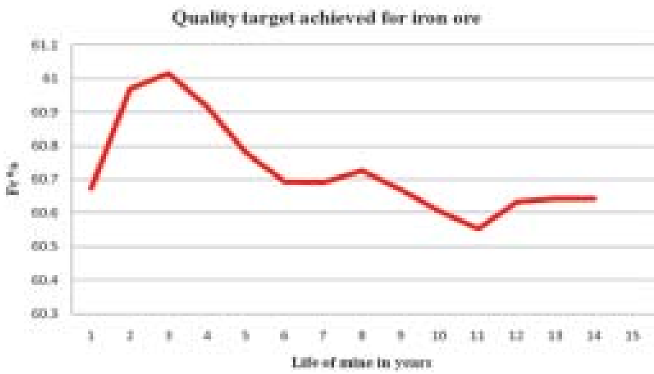

Fig.6 Quality target for Fe %

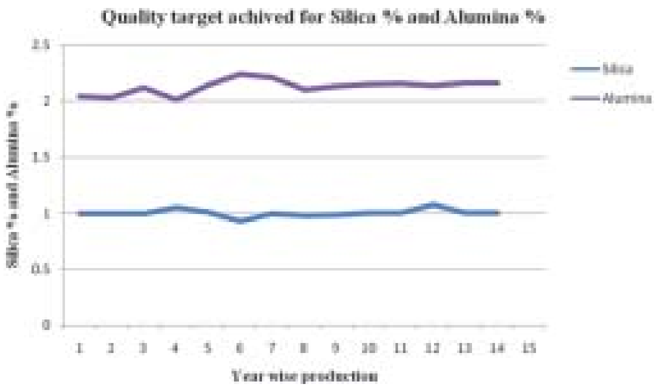

Fig.7 Quality target for Silica and Alumina %

the estimated 75.2 MT of iron ore resource, 50.4 MT is delineated as mineable reserve for the designed ultimate pit limit with overall stripping ratio (mass of waste to mass of ore) of 0.54, simultaneously maintaining the average grade of iron, silica and alumina at 60.73%, 1.0% and 2.12% respectively. Annual production from the mine is fixed at 3.6 MT ROM iron ore for 13 years of mine life. Among the five generated production scenarios, mining direction towards north is preferred because it meets specified quality targets. In addition, significant quantity of overburden can be dumped into the internal dump of the mine that will ultimately reduce re-handling of overburden during the reclamation of the mining pit. Suitable production scheduling for iron ore should focus on optimizing exploitation of mineral deposit that makes the mine profitable, and should supply the raw material uninterruptedly to the dependent industry.

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