Chapter 32

AN INTEGRATED APPROACH TO THE LONG-TERM PLANNING PROCESS IN THE COPPER MINING INDUSTRY

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Abstract Long-term mine-metallurgy planning in the copper mining industry is a complex process that simultaneously establishes ore extraction policies for multiple mines, an investment plan, and an operating plan for processing plants such concentrators, smelters, and refineries. These strategic plans must specify extraction and processing decisions for each cubic meter of mine ore while maintaining their consistency with medium- and long-term objectives.

This chapter demonstrates the advantages and implications of integrated models that can simultaneously plan the entire chain of production from the extraction of ore to the final cathodes, subproducts, and inputs. Little work has been done in this area, which the authors believe is a promising field for development and application in operations research. We begin with a brief description of the long-term mine planning problem in the copper industry and then discuss the advances made in recent years. This is followed by an overview of the copper production process, and finally, a look at the challenges involved in integrated planning.

Keywords: Mine planning, mine scheduling, plant planning, plant scheduling, mixed integer linear programming

1 INTRODUCTION TO THE LONG-TERM MINE-METALLURGY PLANNING PROCESS IN THE COPPER INDUSTRY

The long-term mine-metallurgy planning problem in the copper industry is to establish a strategic plan for production and investment, which ensures a maximum return on investment over a mine's time horizon while remaining consistent with short- and medium factors, and is subject to multiple constraints whether technical (such as the mine's geomechanical stability), environmental, physico-chemical, process-related or of some other type. For large deposits the time horizon will typically be 20 years, but in exceptional cases may be as many as 50.

The planners charged with this task are multidisciplinary groups of interacting specialists who draw up a mine-metallurgy plan, which defines the investment and production schedules for the mines and plants over the entire evaluation horizon, including such items as technology, inputs, processing methods and the scheduled flow of each cubic meter of ore. The result is a document with sufficient detail to be reviewed and audited for consistency and feasibility. Any error at this strategic level could have drastic consequences for the future of the business. A wrongly scaled processing plant, for example, could limit production capacity, while poorly sequenced ore extraction could render unusable significant sections of the mine. In the intimate relationship between the various levels of decision-making, long-term planning is the backbone of medium-term planning, which in turn forms the foundation for short-term planning.

The long-term planning process must find solutions to three main problems:

- Ore deposit production
- Selection, design, and scheduling of investment projects
- Plant operating policy and strategies

Although these problems are simultaneous and highly interrelated, in practice they are solved sequentially and the solution to either of the first two is the input to the next one. This tactic is necessitated by the methodological difficulties involved in a more integrated approach and the fact that even taken individually, the three problems are very complex. Nevertheless, there is general awareness that partial solutions are suboptimal in terms of the overall problem and that their integration would offer major benefits.

In view of the foregoing, the various decisions involved in a mine-metallurgy plan may also be classified into three main categories:

Extraction:

- Which resources to extract and where to transport them. This leads to a definition of the reserves
- When to extract them
- Which technology to extract them with

Investment:
- How much to invest
- When to invest
- Mine extraction capacity and expansion potential
- Plant processing capacity and expansion potential

Processes:
- How each plant should be operated. This includes defining the operating variables
- How much to process in each plant
- Sale of byproducts and intermediate products

Among the technical factors that frame the planning process are sector sequencing, expansions, production smoothing in underground mine production plans, and open-pit slope angles. Other technical issues include observing production rate limits, handling pollutants, and the optimal blend of ore feed to the plants. As regards economic factors, various expected costs and prices over the time horizon including the value of time as given in the plan's discount rate must be considered, and the return on investment and income from products and subproducts such as molybdenum must be maximized.

The evaluation of investments must be approached in a systematic fashion. Examining each project individually is of little use; an investment plan makes sense only if it is harmonized with mine production and processing plans. As the list of projects grows, the difficulties in identifying the combination that maximizes profits while remaining consistent with the mine production plan become increasingly apparent. If we then add the time factor, that is, the scheduling of each of the projects, the decisions associated with both investment and production are clearly a major challenge for planners. All of this gives rise to a set of problems with multiple alternatives and constraints that is large, complex, and difficult to model.

1.1 The Traditional Planning Approach

The long-term planning process for copper mine production and investment begins with the geological exploration of a deposit. The data collected are used to build a geological model in which the deposit is divided conceptually into small ore blocks measuring 20 m^3, and key information such as tonnage, grades, and mineralogical attributes are then determined for each one. Meanwhile, teams of economic experts work on the definition of sales strategies. Specialists in open-pit or underground mine development then define the phases or expansions and extraction points. Multi-disciplinary teams create scenarios for evaluating different investment plan configurations, such as the enlargement of a concentrating plant. The scenarios vary as regards value of ore, planning horizon costs, performance of new technology and quantity and quality of deposits. One or two scenarios are chosen for detailed development in terms of both investments and the production plan.

It should be noted that the optimal operating policy for the processing stages such as crushing, concentrating, and leaching will depend on the volume and characteristics of the ore they are fed. In mine production plans the plant operating coefficients are generally assumed to be constants or linear, a simplification that implicitly supposes a given level of production and set of ore characteristics. However, when developing a detailed plan an optimal operating policy is sought using models that best reflect actual plant operation, whose processes are usually non-linear.

The plan is defined via an iterative process. The planning team attempts to find the best solution by sequentially modifying the investment, mine production and processing plans. Figure 1 illustrates this process and the relationships between each of these constituent plans.

Such an iterative approach leads to feasible solutions that are generally satisfactory, but they could be improved upon through the development of a methodology that effectively integrates the various decisions regarding investments, mine, and plant operation.

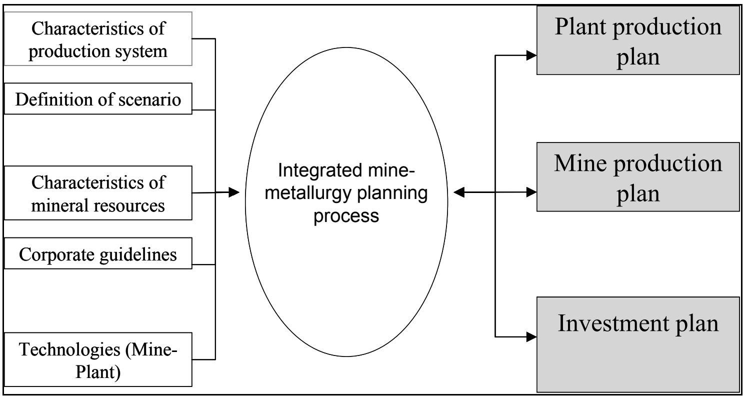

Figure 1. Planning process.

2 REVIEW OF THE LITERATURE

The most commonly cited work on mine planning is that of Lane (Lane, 1988). The author employs economic theory to argue for the advantages of using cut-off grades for defining mineral reserves. His study assumes a simplified operation that enables him to derive simple rules for solving the mining problem in accordance with economic logic. The results may be used as a basis for mine planning in real applications with their singularities and imperfections.

The definition of an optimal pit in an open-pit mine has also been extensively studied. The objective is to find the final pit that maximizes return subject to the physical design constraints. A number of algorithms for solving this problem have been developed over the years, including those suggested by Lerchs and Grossmann (1965), Robinson and Prenn (1977), Underwood (1998), Koenigsberg (1982), Dow and Onur (1992), Zhao and Kim (1992) and Huttagosol and Cameron (1992). Lerchs and Grossman propose an optimizing algorithm based on calculating the maximum flow of a network, Zhao and Kim's algorithm is a variant on Lerchs and Grossman, and Huttagosol and Cameron offer a transportation model approach to the problem. The others are heuristic algorithms that do not guarantee an optimal solution. Hochbaum and Chen (2000) describe some of these algorithms and comment on the most efficient implementations. Elsewhere in this handbook, Caccetta reports on optimization tools that have contributed to a solution.

The long-term mine planning problem has also been tackled using mathematical optimization models. This approach has been increasingly employed in recent years thanks to advances in modeling techniques, solution algorithms, and computer power that have made it possible to deal with complex problems formerly considered intractable. Noteworthy examples in underground mining are the work of Epstein *et al.* (2003), Brazil *et al.* (2002, 2005), Kuchta *et al*. (2003), and Carlyle *et al.* (2001). In the case of Epstein *et al.*, the optimization approach was extended to planning of underground and open-pit mines simultaneously.

Some mining companies, such as Codelco-Chile (Epstein *et al.*, 2003) and Kiruna (Kuchta *et al.*, 2004), have reported positive results using optimization techniques. Other cases have not been published in the literature, possible due to the companies' policy on confidentiality. Studies included in this handbook by Alford, Brazil, Lee and Newman, Kuchta and Martinez (2004) open the way to further progress in underground mining applications.

The mid-1980s saw the appearance of the first studies applying real options theory to the mining problem (Brennan and Schwartz, 1985). This approach attempts to maximize the net present value of future flows generated by a project. Explicit account is taken of stochastic behavior in the principal variables that shape mine planning such as metal prices. Real options theory also allows the incorporation of data from metal futures markets. Unlike more traditional approaches, real options theory does not try to determine a single plan for the planning horizon, but rather seeks to develop a strategy that can be adapted to the values taken on by the stochastic variables. The methodology's heavy demands in terms of calculations and computer power have, however, prevented its use in real-world planning cases, and the solutions found in the literature deal with highly simplified and ideal situations. The main studies in this area are Brennan and Schwartz (1985), Cortazar *et al.* (1998), Schwartz (1997) and Caldentey *et al.* (2006).

This bibliographic overview demonstrates how little, if any, effort has gone into integrating production and plant processes in mine planning. Indeed, we were not able to find a single study that attempted to deal with this issue. In our view, better planning and coordination of the various stages of the mine-metallurgy business has the potential to generate huge opportunities for its improvement.

3 THE COPPER INDUSTRY PRODUCTION PROCESS

Due to the highly specialized and interdependent nature of their assets and the need to be assured of a stable supply of ore for their processing plants, most copper mining companies are vertically integrated from the ore extraction stage to the production of cathodes.

The subproducts obtained will depend on the mineralogical characteristics of a mine's deposits, and the plant processes are calibrated in accordance with the specific conditions they face. There are two types of copper ore, sulfides and oxides. The production line for sulfide ores consists of six stages: mine extraction, crushing, grinding, flotation, smelting, and electrorefining. For oxide ores the grinding, flotation, smelting, and electrorefining stages are replaced by the chemical processes of leaching, solvent extraction (SX), and electrowinning (EW). Each of these stages is described in the following paragraphs.

Extraction: The object of this process is to extract the copper ore from the rock mass in the mine (which may be open-pit, underground, or a combination of the two) and send it for crushing. Low-grade material may be stockpiled for later processing, while very low-grade ore whose processing is not economically viable with current technologies is disposed of in dumps.

Crushing and grinding: The crushing and grinding stages reduce and homogenize the size of the material to particles of no more than 180μm. This is done using a variety of equipment types such as crushers, conventional mills (rod or ball), or SAG mills.

Flotation: The slurry produced at the grinding stage is mixed with frother, depressant, and collector reagents as well as other additives before being sent to the flotation cells. Air bubbles ascending from the cell bottoms attach themselves to the copper particles, which then float up to the top. This yields a marketable concentrate of approximately 31% copper.

Smelting: This stage involves a pyrometallurgical process that takes place in high-temperature furnaces where concentrates with 31% copper content are turned into metal containing 99% copper and separated from any other minerals present such as iron, sulfur and silica. The process has three sub-stages – fusion, conversion and refining – each of which yields marketable products and byproducts.

Electrorefining: Copper anodes are suspended alternately with pure copper cathodes known as starter sheets in electrolytic cells containing a sulfuric acid solution. A low-voltage direct current is applied, causing the anodes to dissolve and the copper to be deposited on the starter sheets. This produces copper cathodes that are 99.99% pure.

Leaching (Oxides): In the case of oxides the process is a chemical one, and larger-sized rock can therefore be used. The ore is arranged in heaps and exposed to sulfuric acid (H_2SO_4), thus generating a copper solution ($CuSO_4$).

Solvent extraction (Oxides): This stage uses selective solvents to separate the copper solution ($CuSO_4$) into one product rich in copper, which is sent for electrowinning and another product containing the impurities.

Electrowinning: This is the last stage in the oxides process. Electrochemical reactions involving a cathode and an anode deposit copper on the cathode.

4 OPPORTUNITIES CREATED BY INTEGRATED MINE-METALLURGY PLANNING

In this section we analyze the advantages accruing to integrated mine-metallurgy planning, based on the notions that the result of one process sets the conditions for the next one and that an investment plan must take into account the entire production chain if the results are to be optimized.

4.1 Mine-Concentrator Planning

Copper sulfide ore is processed in concentrators to yield 31% copper that is then smelted and refined. Since costs and output in the concentration stage depend on the characteristics of the extracted ore, mine planning models should include this process. Incorporating these parameters in mine production planning will enable the overall process results to be optimized. In what follows we describe the most important parameters.

4.1.1 Hardness

The hardness of the ore negatively impacts milling capacity, implying that plant treatment capacity also depends on the plan. Figure 2 is a simple graph of processing capacity (in tpd) as a function of the ore's work index (a hardness measure), illustrating the non-linear nature of the relationship.

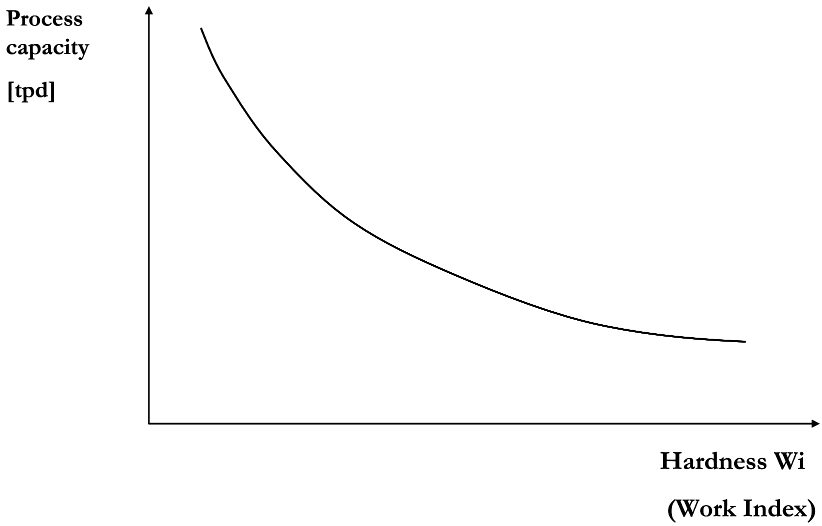

Figure 2. Processing capacity (in tpd) as a function of the work index for a given ore size.

The ore is reduced first by crushing and then by grinding. The mills are classified into conventional, which use steel balls or rods, and semiautogenous (SAG), in which reduction is obtained by collision between the rock particles themselves. The latter method consumes less energy.

4.1.2 Ore Size

Copper recovery at plant level is influenced by the size of the rock feed, which in turn is determined by ore lithology and the crushing and grinding processes. Recovery is greater with smaller rock sizes but size reduction has associated costs, and finding the optimal strategy is not an easy matter. Figure 3 illustrates the relationship; as with hardness, it is observed to be nonlinear.

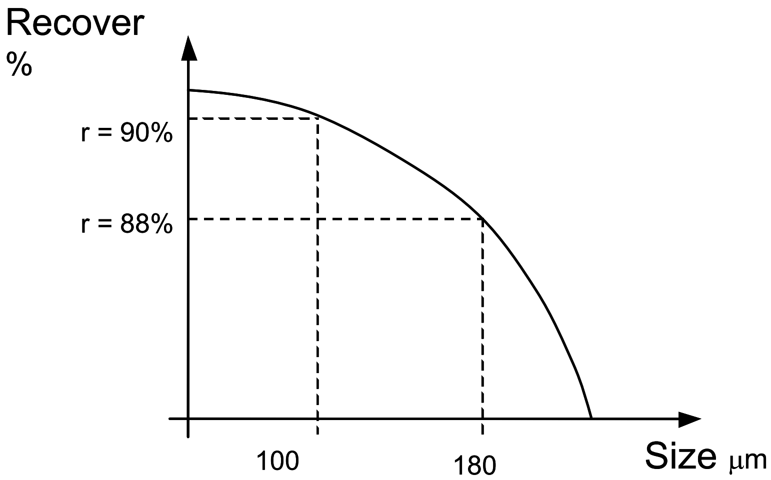

Figure 3. Copper recovery versus ore size.

4.1.3 Pollutants and Impurities

The production of pollutants such as arsenic in the concentration process may limit production capacity and elevate mitigation costs. Pollutant levels can be controlled through the use of an appropriate blend of plant feed to the concentrator, another advantage of integral mine and concentrator planning. Copper ore also contains impurities, many of which have commercial value (molybdenum, silver, gold, antimony, etc.), that should be incorporated into the value maximization procedure. Other impurities merely add costs to the process and their presence should be minimized. Here again we see how a range of variables affect decision-making, and only an integral vision of the entire process will enable company results to be maximized.

4.2 Smelter-Refinery Planning and Its Integration with Mine-Plant Planning

As noted earlier, the production process begins with the extraction of ore from a deposit. Copper may be found in combination with sulfur, forming sulfide ores, or with oxygen, in which case it forms oxide ores. In the case of sulphides, the process involves reducing the rock before sending it to the concentration plant. The output of the plant will depend on the ore size and characteristics. The plant produces concentrates of approximately 31% copper plus impurities and pollutants. Concentrates of molybdenum are also obtained. The planner has various mines or mine sectors to work with, each with its own mineralogical characteristics that strongly impact the result. Concentration plants may be operated in different ways, prioritizing variables such as copper production, metal recovery, minimization of pollutants, or some combination of these.

The copper concentrates are fed to smelters that produce mainly copper anodes with a purity of 99%. They also produce blister copper and white metal, intermediate products that may be marketed or further processed to obtain anodes. These are then sent to a refinery where they are purified to obtain cathodes of 99.99% copper. Anode bars containing commercially valuable impurities such as gold, silver, antimony, and bismuth are also produced. The gases given off by the furnaces are sent to a gas cleaning plant for dust abatement and production of sulfuric acid.

In the case of copper oxides, an alternative process known as leaching generates a single marketable product, which is copper in the form of cathodes. It is generally cheaper than the traditional concentration and smelting-refining process.

The processes described here are shown schematically in Figure 4.

4.2.1 Integration of Input Supply Logistics and Sale of Products in the Smelting-Refining Process

Given the high cost of ore transport, concentration plants and leaching facilities are located relatively close to deposits. Smelters and refineries, on the other hand, may be installed relatively far from the ore source. This is due to the higher value added of the inputs such as concentrates, white metal, blister copper, and anodes, making their transport relatively efficient. Some plants are situated near railway lines or seaports to facilitate the shipping of products and delivery of inputs.

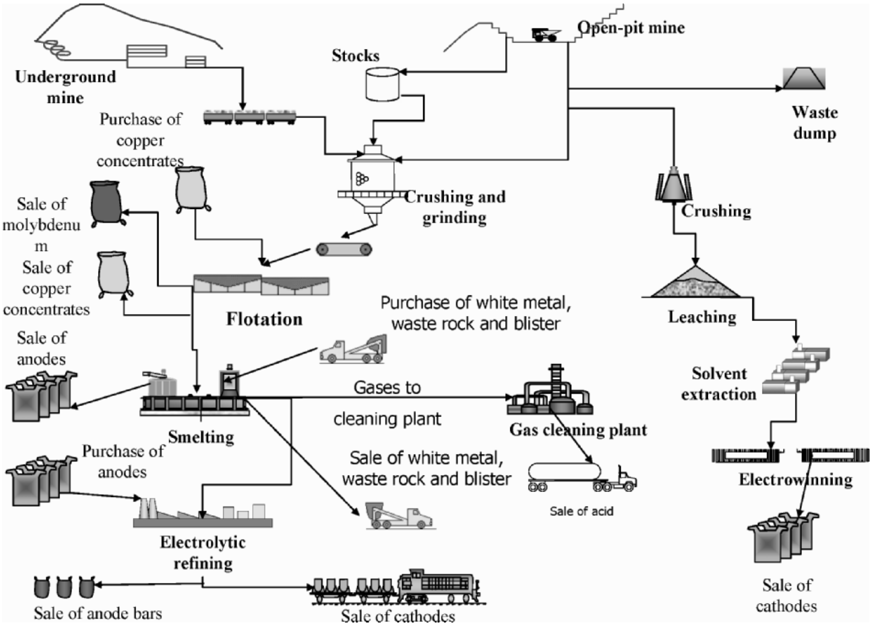

Figure 4. Schematic diagram of process.

Although the smelting-refining process is usually integrated with the overall mining business, particularly in large companies, in some cases it is a separate business managed independently of any particular ore deposit, and functioning as a business center that markets commercially valuable products and subproducts generated by the process such as sulfuric acid, anode bars, molybdenum concentrates, blister copper, and white metal.

The efficient running of a smelting-refining operation consists in optimizing input supply logistics and maximizing return on the portfolio of products. This includes skillful marketing management and plant planning that is also market-focused with a view to determining the optimal mix of products and prices. Needless to say, optimal operation of the physico-chemical plant processes is also necessary.

To optimize input supply to the plants it is essential that every alternative be evaluated, taking into account the cost of raw material, transport costs, and the metallurgical characteristics of the inputs. Similarly, to maximize returns on plant products we must evaluate the options in the various markets, considering price, transport cost, and market size.

An efficient way of carrying out such evaluations is through the use of optimization models that focus on maximizing returns from product sales less transport and production costs. These models generally have a linear structure and include the subproblem of input and product transport. Certain commercial constraints in addition to technical constraints on production capacity are also incorporated. These models are highly useful in ensuring efficient input and sales management that could form the basis for a strategy of running the plants as profitable business units.

4.2.2 Limiting Factors in Copper Production

Certain aspects of energy and water resources constitute limiting factors on copper production. The demand for these resources is directly related to mine and plant production levels. Tables 1 and 2 summarize relative water and energy consumption for the various stages of the production process.

Table 1. Relative consumption of water resources by stage.

Process	Consumption (%)
Crushing-grinding-flotation	53
Smelting	10
Hydrometallurgy	15
Other	22

Table 2. Relative consumption of energy resources by stage.

Process	Consumption (%)
Crushing-grinding-flotation	48
Fundition	19
Refinery	4
Others	29

Water is a scarce resource whose value is rising. Some major copper deposits are located far from any water source, as is the case in Chile where most production is found in the Atacama desert. In other cases, environmental regulations restrict the use of water resources for industrial purposes. In practice, water consumption is a limiting factor on copper production, and planners face a real challenge to correctly assign water resources in such a manner as to optimize the value of the business. A poorly conceived or shortsighted assignment could have a drastic impact on the business and limit production.

Energy inputs and their associated costs are also significant limiting factors in the planning process, and energy variables affect strategic decisions in both the design and operation of a mine. As an example, changing from open pit to underground mining is a decision that can be justified by energy savings given that as the pit becomes deeper the increase in truck fuel costs to haul the ore to the surface may render the operation noneconomic. Another example is the very energy-intensive grinding and crushing operations, whose energy consumption depends on the degree of size reduction required and the hardness of the ore. Planners can improve both variables by looking at the entire business when optimizing its value.

In the smelting-refining stage, the most serious limiting factors are those relating to environmental pollution. The main pollutants generated by these processes are arsenic and sulfur. In order to protect the environment and comply with legislation on the subject, mining companies are required to treat these residues and mitigate their negative effects. Treatment capacity and the associated costs are thus limiting factors in mine-metallurgy planning. If these constraints are active, planners can choose higher tonnages of lower-grade ore containing fewer pollutants in order to increase total refined production.

The three resource variables just discussed – water, energy and the environment – must be carefully considered in the planning process, as they can significantly limit the production derived from an ore deposit. In some operations, these resources are not properly valued, leading to their overexploittation or inefficient use and consequent harmful effects in the medium term.

5 CONCLUSIONS

Mine-metallurgy planning must deal with three principal issues: an investment plan, processing plant planning and mine production planning. Although they arise simultaneously and are closely interrelated, in practice they are dealt with sequentially and the solutions adopted for one is the starting point for solving the next.

This sequential procedure is adopted because of the methodological difficulties involved in a more integrated approach to what are already highly complex problems when considered individually. Nevertheless, there is general awareness that separate solutions are suboptimal in terms of the overall problem, and integration would yield great potential benefits.

Operations research in the copper industry has primarily focused on solving mine production planning problems, with good results for both underground and open-pit operations.

Among the principal challenges facing operations research in mine-metallurgy planning is the development of methodological approaches that make it possible to integrate investment, plant, and mine production decisions so that strategic plans create greater value and optimize the entire copper production chain.

Another significant challenge is an improved incorporation of the various risks inherent in a long-term mine-metallurgy plan.

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