LONG TERM OPTIMIZATION OF INVESTMENT AND PRODUCTION PLANS IN OPEN-PIT AND UNDERGROUND COPPER MINES

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ABSTRACT

Since 1999, Codelco and the Department of Industrial Engineering of the University of Chile have been collaborating in the development of a computational system to optimize long term mining plans. The first optimization model was developed and implemented at El Teniente, the largest underground copper mine in operation. The model was formulated based on a network-flow approach, starting at the extraction stage at the block level, and considering at the end all the downstream processes such as crushing and concentration. A second model with similar characteristics was implemented at the company's open-pit mines in the north of Chile. Today, both models have been integrated into a single computational system that can be used to evaluate production plans of a complete division with several mines, either underground or open-pit, that might share processing stages (e.g. a concentration plant) and/or means of transportation (e.g. a railway network). The system has become an essential component of the planning process that has consistently increased the value of the company.

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INTRODUCTION

During the 90s there was a substantial increase in the world-wide production of copper, especially in Chile, where the production between years 1990 and the 2000 increased by 189%. Such trend has continued in the last decade, with a 70% growth of Chile’s production from 1996 to 2005, whereas the world-wide total has only increased by 35% in the same period.

Chile is the main copper producer in the world, with a production of 5.3 million tons of fine copper in year 2005, equivalent to 35% of the world-wide total, and with 38.4% of the total known reserves. The sector reported to the country exports by a total of 21,817 million dollars in 2005. The expectations in year 2006 are even higher given the upwards trend of copper price.

Among Chilean mining companies, Codelco stands out as the largest copper producer on the globe. With a production of 1.7 million tons in 2005, Codelco is organized in five divisions, each one of them having multiple deposits and processing facilities.

The present challenges faced by Codelco are related to increasing their productive capacity and its efficiency. This means large investments in the productive system, as the construction of new processing plants and the incorporation of new mineral deposits. These structural challenges also imply challenges in the production planning process. In particular, nowadays, an integrated approach is required that allows generating long term production plans that effectively combine multiple deposits and plants, with the objective of maximizing total economic value. The traditional planning scheme was typically focused on locally optimizing individual operations, neglecting the essential interactions among them.

Currently, existing facilities and different investment projects, as for example the extension or construction of new plants, compete for mineral and financial resources. The interrelations between the different projects, added to the intrinsic complexity of mining operations, make the planning process a key managerial issue in the mining business.

This article is based on the ongoing collaboration between Codelco and the Department of Industrial Engineering of the University of Chile during the last 7 years. This team has developed and implemented a computational optimization system, which is arguably one of the most novel proposals in the industry.

The paper has the following structure: The remainder of this section has brief literature review. In the next section we first describe the main challenges encountered in long term production planning in the mining industry, and then we introduce our methodology and we provide an overview of the model’s implementation. In the third section we describe the overall impact the model has reported until now, and in the final section we conclude.

Literature Review

Most optimization models available in the literature have been developed for open pit mines and they solve only a partial version of the long term planning problem. In fact, the majority of research efforts have concentrated on determining the economic mineral reserve in an open pit mine. This is known as the ultimate pit problem. There are two main approaches to solve this problem. One is based on cutoff grades and the other one is based on Operations Research (OR) techniques. The optimal cutoff grade methodology was made popular through the work of Lane [1]. It can be applied to either open pit or underground mines. The concept of optimal cutoff grades is simple but powerful. Moreover it has important operational advantages and is embedded in the background of all mining practitioners. The drawback is that finding the optimal cutoff grade is not trivial. This methodology was adapted to the reality of El Teniente by De la Huerta [2] and was used extensively to generate long term production plans, as for example, the annual *Base Case Report* [3] in years 2000-2003, but the analysis of one particular scenario could take several weeks. Another practical application of Lane's methodology can be found in Poniewierski *et al* [4].

The use of OR techniques to solve the ultimate pit problem started with the classic "moving cone" heuristic (see for example Kim [5]), which can be suboptimal but is intuitively appealing. Among the algorithms with a proof of convergence to optimality, historically the most important are Lerchs and Grossmann [6] and Picard [7]. The first one is based on graph theory but it can be shown that its structure is very similar to the dual simplex algorithm (see Underwood and Tolwinski [8]). The second one proves the equivalence of the ultimate pit problem and finding a maximum closure in a graph. Therefore, it reduces to a maximum flow problem that can be solved, for example, with a push-relabel procedure. A good explanation and comparison of both procedures together with a complete literature review of the ultimate pit problem can be found in Hochbaum and Chen [9]. Even though such efficient algorithms exist, the problem itself does not consider what happens with the mineral beyond the extraction stage and, for instance, does not provide a production schedule that considers all the downstream capacities.

Beyond the design of the ultimate pit, OR techniques have been used to solve the corresponding production-scheduling problem. For example Tolwinski and Underwood [10] propose a dynamic programming approach while Gershon [11] uses mixed integer programming. See also Sevim and Lei [12], Caccetta and Hill [13], Sarin and West-Hansen [14], and all references therein. In the case of underground mines, two important pieces of work are Kuchta *et al* [15] and Newman *et al* [16]. Both cover the same topic, the implementation of a production scheduling mixed integer program at LKAB's Kiruna Mine. The first paper presents the model and the preliminary results and the second one explains additional pre-processing routines that significantly reduce the size of the problem. These papers are related to ours even though their model only copes with the scheduling problem and the objective is to minimize the deviation from pre-specified demands per period. The sizes of the instances are not comparable either but there are some similarities in the modeling and the techniques used to reduce the size of the model.

Several other applications of OR methods to specific (open pit) mining problems are described in Caccetta and Giannini [17], including the determination of optimal blends or the determination of equipment maintenance and replacement policies, However, very few papers can be found with mathematical models that try to solve the long term planning problem in an integrated fashion. One attempt would be Dagdelen and Johnson [18] but the instances are still small compared to real-life cases. Another example is Barbaro and Ramani [19] where discrete optimization is used to solve a facility location model that also decides if a sector of a mine should produce or not. It assumes that the economic mineral reserve has somehow already been defined and takes it as an input. To the best of our knowledge, the most closely related paper to our work is Carlyle and Eaves [20]. Their mixed integer model was developed for an underground platinum and palladium mine and considers several mine planning decisions, including development, drilling, preparation, and production of each mine segment for an horizon of 10 quarters. However, the model is relatively small compared to ours and near optimal integer solutions can be obtained with a commercial software package.

METHODOLOGY

Long term mining plan

A long term mining plan consists of a detailed specification of each aspect related to investments and production in the mines and plants including technology, raw materials, processing procedures, and an extraction schedule and destination for each cubic meter of mineral. This plan must be coherent with respect to the company's short, medium and long term aspirations. The importance of the plan stems from the fact that most decisions are final and cannot be reversed, meaning that they can drastically affect the future of the mine. For example, poor capacity choices at the concentration plant or selecting an inappropriate extraction sequence can trigger a significant yield decrease.

Figure 1 shows a schematic description of the decision ladder for a generic mining company. The strategic plan, which provides the relevant scenarios to be considered and the overarching business guidelines, is a fundamental pillar for medium term planning, and the latter plays a similar role when it comes to making short run decisions.

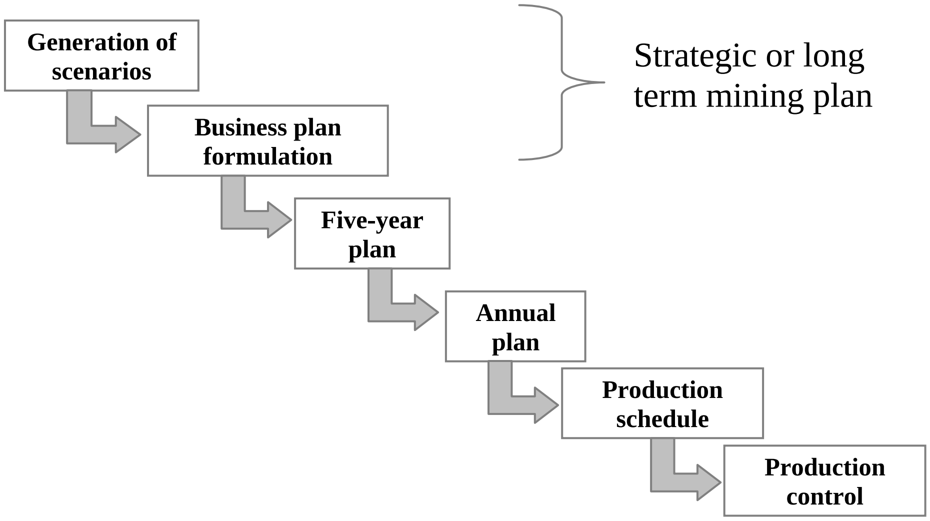

Figure 1: Schematic description of the decision ladder in the planning process.

The long term planner must solve three main problems:

1. Extraction: production in the mine.
    - What reserves to extract?
    - When to do it?
    - With which technology?

2. Investment: selection and timing of investments.
    - When to make investments?
    - Fleet sizes.
    - What is the optimal capacity of the plants?

3. Processing: operation of the plants.

- How much to process?
- Sale of by-products.
- Sale of intermediate products.
- Water and power requirements.

Solving each one of these problems, even separately, is already a complex task. Hence, solving them simultaneously in an integrated manner taking into account the interactions can easily become a problem out of reach for traditional planning procedures. New methodologies must be developed to face this challenge, and an interdisciplinary team must be in charge with different specialists that contribute complementary experiences, knowledge and skills.

The need of an integrated planning approach cannot be dismissed. For instance, in the case of investment decisions, these are usually associated either to the incorporation of new extraction areas or to increases in processing capacity (e.g. an increase in the cargo capacity or an extension of the concentration plants). However, the evaluation of different investment projects cannot be done in isolation. Each project analyzed individually might not seem profitable. The real value of an investment project is only appreciated once its coherence is verified with respect to the extraction and processing decisions. Moreover, when the list of projects begins to grow, it is difficult to identify the combination that maximizes the company’s profits. If in addition we add the time dimension, i.e. the exact starting date and duration of each project within the planning horizon, it becomes evident that a non-integrated approach can only lead to suboptimal outcomes.

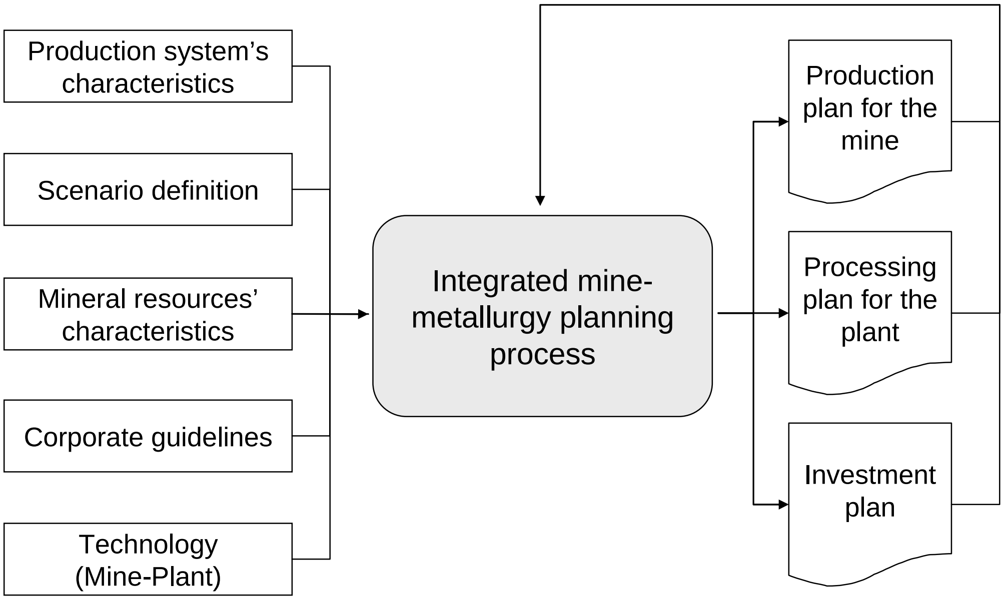

Figure 2: Description of the integrated planning process.

The set of inputs and outputs of the integrated planning process that we advocate are depicted in Figure 2. Since most mines Codelco owns are particularly large, the planning horizon must also be large, typically between 20 and 50 years (life of a mid-size mine). The resulting plan should be given detailed per year, indicating the investment decisions, the operation of the plants, the extraction of reserves and the flows of materials. Moreover, the plan not only must be economically profitable, but it also must be technically impeccable. This means, among other things, that is has to comply with the geotechnical rules that govern the mine, it must consider constraints due to the chemical processes at the plants, it must meet environmental regulations, and it should guarantee that downstream capacities will not be exceeded.

We conclude this subsection with a summary of the nine main elements we have identified that complicate the elaboration of long term mining plans. These elements are associated to the complexities of the planning problem.

i. Multiple mines that compete for limited processing and transportation capacity.

Metallurgical plants have limited capacity for which the blocks of material of multiple deposits have to compete. Each block has different extraction costs, processing costs, tonnages, copper grade and intrinsic economic value. However, the convenience of processing a block depends on the characteristics of the block at issue and the characteristics of the other blocks of the mine, that also compete to be processed.

ii. Long planning horizons.

The production of copper is a long term business that requires large investments that are typically only recovered after many years of operation. Therefore, mining plans must be elaborated for long planning horizons, generally 20 to 50 years, which considerably increases the number of alternatives to consider. In addition, the decisions in a given period will affect the conditions of the mine in the following period, and consequently, also the future decisions.

iii. The benefit of a mineral block also depends on its location in the mine.

The benefit of a mineral block depends not only on its grade, tonnage and recovery, but also on its relative location in the mine. That is why the extraction of a low grade block can be advisable because, once removed, it might allow the extraction of higher grade blocks. Similarly, a low grade block that is near a concentration plant can be more profitable than a richer block that requires more transportation.

iv. Handling stocks of mineral.

The possibility of keeping material inventory allows the planner to improve the company’s yield, since processing decisions can be postponed until the most advisable moment, possibly several periods after extracting it. In economic terms, the competition for the capacity of the plants happens between the material in the mine and the one in stock. Hence, the competition for capacity is also across periods and the planner must handle inventories judiciously to take advantage of the postponement opportunities.

v. Laws of physics that govern mining operations.

The extraction of material in underground mining or in an open-pit must comply with the laws of physics that govern such geological interventions. In the underground case, the extracted material flows downwards following the gravity force. The design of these mines is technically sophisticated to maximize the flow and to avoid a collapse of the tunnels and underground facilities. In open-pit mining there are also several difficulties, for instance the risk of walls sliding down into the active area. These factors, along with others like the subsidence, the regularity of the operations, the safety measures and rate of extraction, contribute an important dose of complexity to the work of the planners.

vi. Multiple destinations for extracted material.

The material that is extracted from the mine can be sent to processing or inventory. If it is sent to processing, again multiple alternatives might be available, like leaching or the traditional process of concentration and smelting. In each case there are several plants to consider as different options. Each one of these options has different processing costs and technical factors that determine the yield, together with different transportation costs. This range of alternative destinations enriches the possibilities of the planner, but it also makes it more difficult to find the optimal solution.

vii. The problem of planning at a large scale.

In this paper we claim that the long term mining plan must integrate decision between mines and processing plants in order to obtain a roadmap that optimizes the global result of the company, and not a local process or activity. Such approach increases the size of the problem translating into a huge number of variables and constraints. Without doubt, the order of magnitude of the problem is another characteristic that adds hurdles to the planning process.

viii. Transformation of open-pit to underground operations.

This one is a common issue at the planning stage. In a nutshell, it is nothing but the usual fixed versus variable cost dilemma. It is part of the planner’s tasks to find the breakpoint when the operations should switch from one mining method to the other. In the case of Codelco’s North Division, there is constant interest in assessing the trade-off between open-pit and underground operations for the Chuquicamata and Mansa mines. For example, if the planner evaluates Chuquicamata’s current operations without considering the possibility of continuing as an underground mine, then the outcome would probably be a larger open-pit with an inevitable increase in variable costs.

ix. Additional constraints.

Most companies have additional internal and external policies that must be followed. For instance, rules related to environmental policies, sustainability, financial risks, production targets, and safety levels among others. These additional constraints certainly complicate the problem formulation and its resolution.

Model Formulation, Solution and Implementation

The following are the key features of the unified model we propose:

- We suggest a math programming approach with two main parts: one representing the mining resource (reserves); and one representing the network of processes where the mineral flows and in which alternative technologies of operation and/or investments can be considered.

- The basic modeling unit of the mining resource is a block (the same ones from the geological block model). A binary variable is associated to each block in each period indicating when it will be extracted.
- The planning horizon is set somewhere between 20 and 50 years, with shorter periods at the beginning (when more detail is required and deviations in the production have a major impact in the results), and longer periods towards the end.
- The objective function is to maximize the net present value, i.e. discounted benefits (obtained from the sales of the final products) minus discounted variable and fixed costs.
- Three different ore products are considered: copper, molybdenum and arsenic. The first two are commercial products while the last one is a pollutant on which additional constraints may be imposed.
- The equipment, machinery and facilities that are “consumed” during the planning horizon are prorated and included as variable costs.
- All the processes posterior to the ore extraction are modeled as a capacitated network design/flow problem. Then future investments translate into alterations of the existing capacities and/or additional nodes and arcs in the network.
- In underground mining, the main stages (nodes) of the network are crosscuts, ore passes, crushers, mills, and concentration plants. The arcs represent the existing means of transportation between nodes.
- In open-pit mining, the main stages (nodes) of the network are waste and stocking areas, crushers, mills, and several types of plants (flotation, leaching, bioleaching, and dump). As in the underground case, the arcs represent transportation alternatives.

Figure 3 provides a schematic representation of the mathematical model just described. In order to obtain a technically feasible solution several mining constraints must be added, for instance:

- Minimum extraction: depending on the ore’s properties there exists a minimum level of extraction to avoid the formation of solid rock pillars or to remove a layer of waste.
- Rate of extraction: upper and/or lower bounds may be set depending on the characteristics and current state of each sector.
- In underground mines the extraction must be even and smooth to allow a correct breaking of the rock. Moreover, the opening of the extraction points must comply with a pre-specified sequence along with geological/mechanical considerations and possible interactions among different sectors (subsidence).
- In open-pit mines, a critical constraint refers to gradually sloping pit walls to avoid sliding of waste material.

Following the methodology just described, we developed a computational system that is based on four components, as it is depicted in Figure 4. The first component is the user’s interface, where the planner interacts with the system. The second component pulls the information from a data base and calculates the technical coefficients required as parameters in the optimization problem. The third component formulates the model and solves it. The fourth component generates the different reports from the solution, each one of them with different purposes and final user.

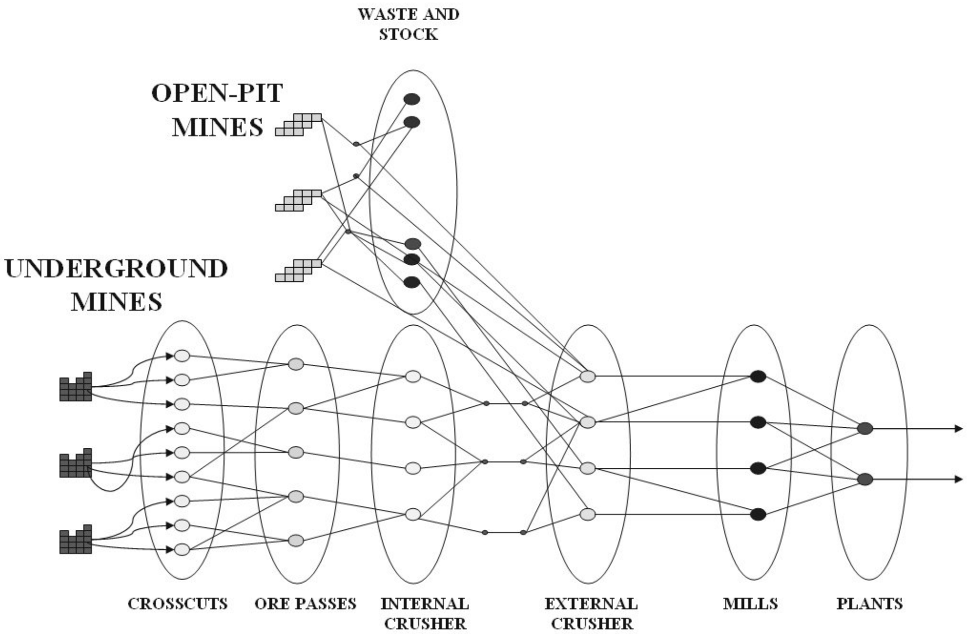

Figure 3: The extraction stage and the network of intermediate processes for underground and open-pit mines

The resulting optimization problem is difficult to solve, even using last-generation computers. Therefore, the algorithm in the third component of Figure 4 consists in solving a linear relaxation of the model and then performing a heuristic local search in order to find an integer feasible solution. In practice, our algorithm finds near optimal solutions in relatively short running times. Note that this methodology would be valid and effective also in the case of other minerals different from those extracted by Codelco.

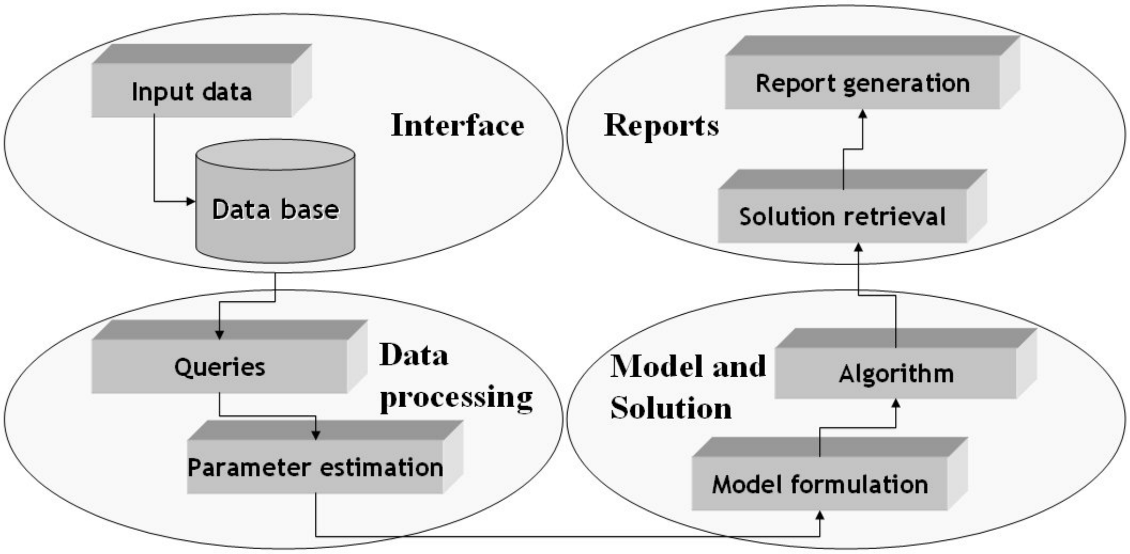

Figure 4: Computational system to optimize long term mining plans.

RESULTS AND DISCUSSION

In the case of the underground mining, our methodology allows a better selection of the material to extract, which is a key issue in this type of operation. We conducted an experiment, reported in the Copper Conference 2003 [21], where we compared the results of the traditional planning procedure and the one based on the integrated optimization model here described for the underground mine at El Teniente Division. The comparison was done considering the same investment projects in both cases, that is to say, only varying the selection of reserves. The optimization model reported a NPV gain of 5.1%. Noteworthy, the increase in NPV would have been even greater if the model had been able to choose the plan of investments.

In open-pit mining, the selection of reserves is less relevant since all the material (either ore or waste) is extracted. In this case, the main concern is to decide the appropriate destination (waste, stock, or grinding) for each cubic meter of extracted material in each period, where the destination determines the transformation process that the material will undergo. In addition, the plan includes the investments, timed accordingly, that enable the flows and processing. For the case of an open-pit mine we have not performed a benchmark experiment as the previous one, but preliminary results reported in Goic [22] suggest that the benefits would be similar.

This project began at El Teniente Division of Codelco. To date, the system is being used, with varying degrees of intensity, in all of Codelco's divisions. The model can evaluate plans much faster that the traditional approach. This has allowed the planners to examine a larger number of scenarios and to explore several combinations of investment and operational alternatives. In particular, the computational system is being used at Codelco's North Division to evaluate the integrated plan for the Chuquicamata (open-pit and underground), Radomiro Tomic, Sur, and Mansa mines, considering different configurations in terms of concentration plants, leaching, bioleaching, cutoff waste grades, stocking areas and dumps. The implemented system has been an essential tool in the development of the strategic plans from 2004 onwards (known as the PEX/PND plans). The system has played a crucial role in the planning process, having rendered in addition support to other strategic projects like the extension of the concentration plant and the conversion of Chiquicamata to underground mining.

CONCLUSIONS

Generating long term mining plans is a complex task, with many variables and constraints that interact in multiple dimensions. To solve this problem, an interdisciplinary team of the Department of Industrial Engineering of the University of Chile, together with professionals from Codelco, has developed and implemented in recent years a methodology based on an optimization model to support the planner's decisions. The results to date are promising, obtaining significant benefits that can be summarized in the following points:

- Integrated long term analysis of multiple mines and plants.
- Quick analysis of multiple scenarios and restrictions.
- Search of an optimal plan for each scenario.
- Evaluation of investment projects.
- Optimal timing for critical investment projects.
- Dynamic routing to stock, low grade, and dump areas.

The results of this work show the benefits of the collaboration between universities and private companies. On the one hand, part of the mission of the university is to generate relevant and useful knowledge for the society. On the other hand, companies must innovate looking for the best technologies and the best managerial practices. It is, therefore, of mutual benefit to generate the virtuous circle that enables research and innovation contributing to universities, companies, and the society as a whole.

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