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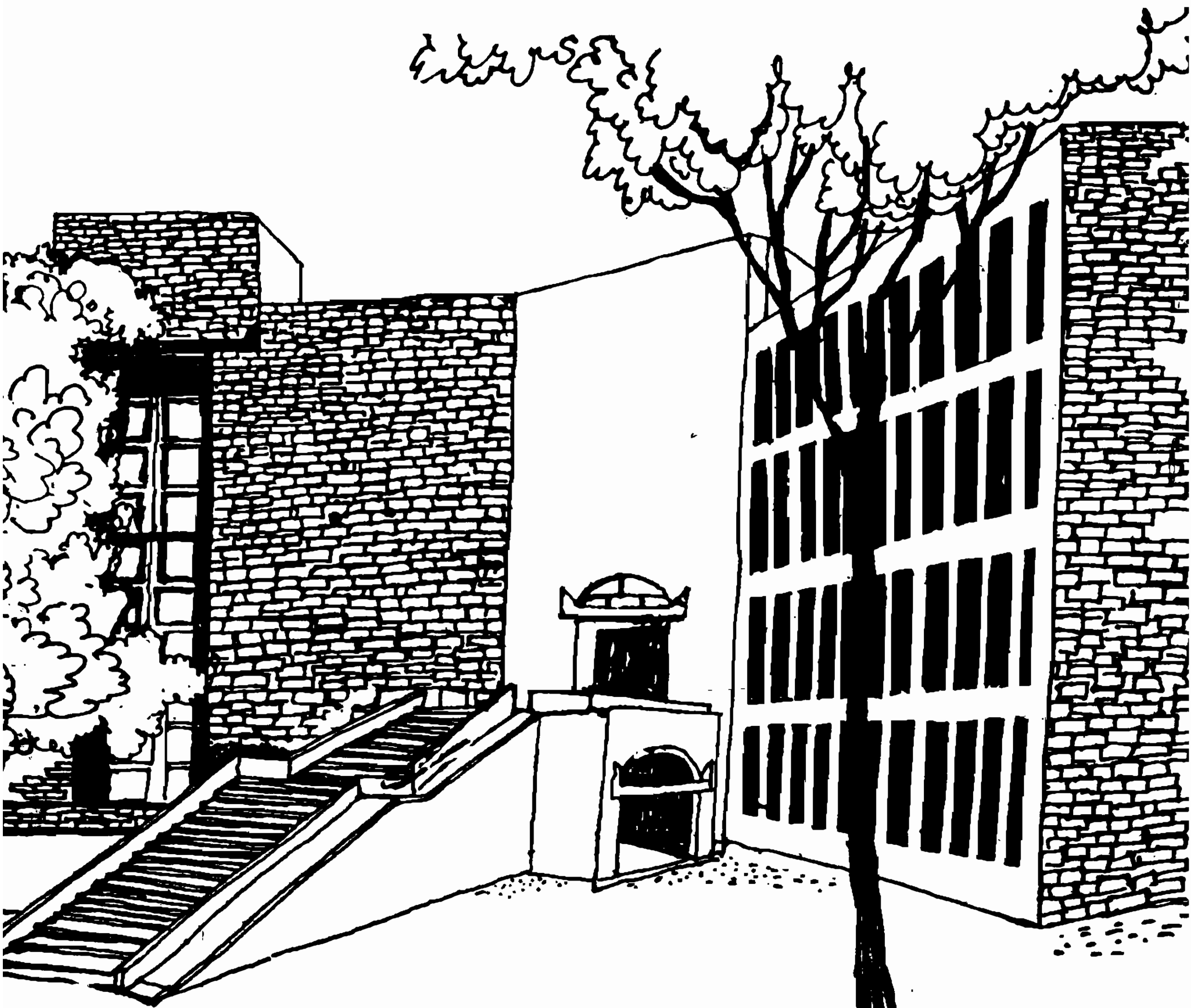

A SURVEY OF MATHEMATICAL PROGRAMMING APPLICATIONS IN INTEGRATED STEEL PLANTS

By

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A Survey of Mathematical Programming Applications in Integrated Steel Plants

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ABSTRACT

Mathematical programming techniques were used in the steel industry as early as 1958, and many applications of optimization in steel production have been reported since then. In this survey, we summarize published applications in the largest steel plants by type, including national steel planning, product mix optimization, blending, scheduling, set covering, and cutting stock.

 We gratefully acknowledge financial support from the American Iron and Steel Institute and another American steel company.

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1. Introduction

An integrated steel plant is a complex industrial system in which numerous products are routed through different series of production units. The sales, cost, and net profit of each product are functions of many variables. If the operating manager makes decisions that result in sub-optimal operations, a significant savings or income opportunity can be lost. In this paper, we survey mathematical programming applications to the following classes of problems in integrated steel plants:

- National steel planning
- Product-mix optimization
- Blending in blast furnaces, coke ovens or steel foundries
- Scheduling, inventory and distribution
- Set covering
- Cutting stock optimization

Applications in fifteen different countries in four continents have been reported from 1958. Prior to our current paper, there have been four surveys. Mihailor (1961), which surveys 34 papers, is an elementary aid for engineers and metallurgists. This survey also gives an overview of how linear programming models can be applied in a steel plant. Gercuk (1961) is a non-mathematical survey devoted to the subject of linear programming and some of its applications, mainly in composition of charges, loading of equipment and transportation of equipment. The work by McCulloch and Bandopadhay (1972) gives a broad overview of operations research models, a significant proportion of which are in the areas of mathematical programming and large-scale optimization. A study by Rao *et al.* (1993) gives a classificatory review of OR applications in strategic planning, operational planning and tactical planning.

The paper is written for two audiences. The first is the management science practitioner in industry who is looking for possible areas of applications of optimization techniques in an integrated steel plant. The second is the academic researcher who is looking for potential research areas in integrated steel plants. An elementary knowledge of integrated steelmaking operations is desirable, but not essential. The reader interested in acquiring a detailed knowledge of iron and steel production is referred to AISE Steel Foundation (1998).

In this paper, we consider all of the front end of integrated steel making operations, from iron-making to finished steel production, but have not considered applications in mines and quarries. Emphasis has been placed on the real world implementation of the models. A brief description of an integrated steel plant is given in Section 2, prior to the survey in sections 3-9.

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2. An Overview of an Integrated Steel Plant

Figure 1 describes an iron and steel making plant having four stages: iron making, steel making, primary rolling and finishing rolling. The output of each stage becomes the input to the following stage. In the iron making stage, the blast furnaces are used to convert iron ore, sinter and other raw materials into molten iron called hot metal. Hot metal is supplied to the steel melting shops where the process of steel making is either BOF (Basic Oxygen Furnace), OHF (Open Hearth Furnace) or EOF (Energy Optimizing Furnace). The molten steel from BOF is either sent to the continuous caster or poured into various ingot molds. The molten steel from other shops is cast into ingots.

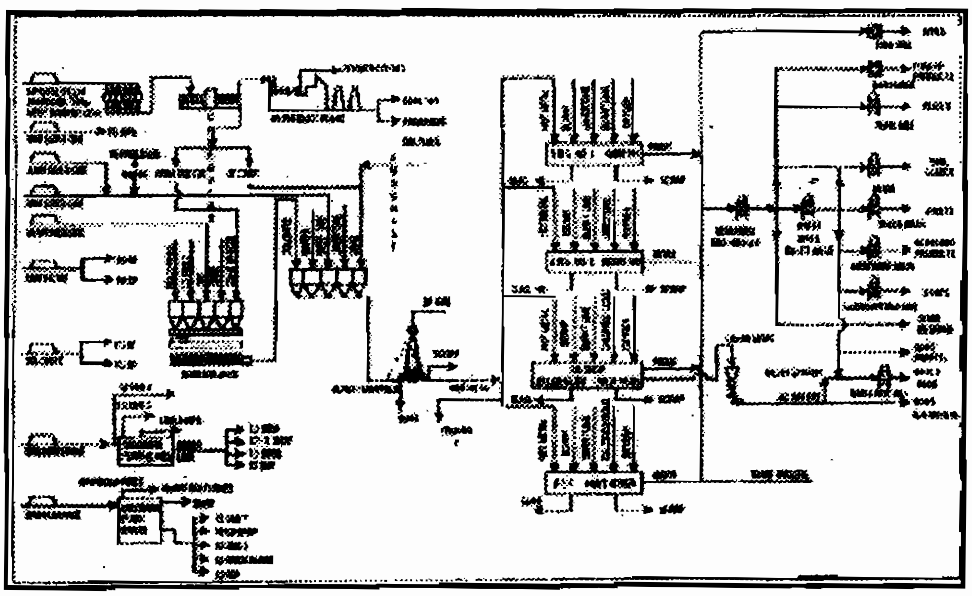

Figure 1. Diagram of flows through an integrated steel plant.

In the primary rolling stage, ingots are shipped to the soaking pits where they are heated by a mixture of gases to a uniform temperature, before being rolled into blooms and slabs in the Blooming Mill. The blooms are further rolled in the Sheet Bar and Billet Mill into either sheet bars or billets. In the finishing rolling operation, the slabs, sheet bars, strip bars and billets are the input materials to various finishing mills. The slabs are rolled in the Plate Mill into high tensile and wear resistant plates or ordinary mild steel plates. The sheet bars are further rolled in the Sheet Mills into high silicon, LPG (Liquid Petroleum gas) and galvanized sheets. The Strip Mill converts the strip bars into cold rolled or ordinary strips which go either to the market or the Tube Making Plant.

Billets from the Sheet Bar and Billet Mill go either to the conversion agents or to the Merchant Mill where they are rolled into twisted bars, angles, octagons. The blooms are further rolled into seamless gothics (for seamless tube-making) or into structurals in the Medium and Light Structural Mill.

3. National Steel Planning Models

Before describing applications developed for specific integrated steel plants, we mention in this section several steel planning models for national economies, using linear programming techniques.

National Steel Planning Model in the United States

Tsao and Day (1971) develop a process analysis model of production in the US on a national level. A technology matrix, which represents the technology structure, is estimated using engineering and metallurgical information. This matrix together with the detailed cost, sales and revenue figures is then used in a linear programming model of short run allocations of the steel industry as a whole. The linear programming model is then obtained and compared with available industry statistics for each year from 1955-1968. Although Tsao and Day claim to have a fairly good results, a later study by Nelson (1971) reported that the model had an error in the treatment of coking coal production. Nelson attempted to correct this deficiency and presented a correlated matrix for this stage of production.

Mexican Steel Model

This study by Kendrick, Meeraus and Alatorre (1984) develops two static models for production planning and one dynamic model for investment analysis. The two static models, formulated as linear programming models, are mixed production and transportation problems. Inputs are prices of raw materials, operations and shipments, demands, facility capacities and input and output coefficients for each productive unit. Outputs are optimal product distributions. The dynamic model, formulated as a mixed integer program, incorporates time factors and deals with the investment issues in five time periods of three years each. The inputs are similar to those in the static models but output also includes investment decisions.

Stochastic Programming Model for Investment Planning in India

Anandalingam (1987) discusses a stochastic programming model for investment planning in environments where demand projections and technological coefficients are not known with certainty. The model has been used primarily for strategic planning rather than operational planning. The usual programming formulation of an industrial process is extended to incorporate parameters and demand uncertainties by modeling it as a stochastic linear program with simple recourse (SLPR). The SLPR is solved using the less restrictive assumption that only the means and variances of the stochastic entities (but not their distributions) are known. The methodology is applied to the study of the steel industry in India with a novel way of modeling investment and economies of scale.

4. Product-Mix Optimization Models

In an integrated steel plant, the problem of determining the optimum production level at various stages is of great practical importance. This is so because the profit is sensitive to the product mix and not merely to the total volume of production. Because of the complexity, sub-optimal workable solutions are generally obtained by experience. Although these solutions when implemented achieve good plant utilization, profits/revenue from these solutions are considerably less than the potential profit/revenue that could have been accrued using the optimum product mix. The optimum product mix changes from month to month and with the mill, furnace availability, and demand for the product in the market. Pioneering work in this area by Fabian (1958) was undertaken at Kaiser Steel Company, and since then a number of applications in this area have been reported.

Product-Mix Model at Kaiser Steel Company

An integrated steel plant has a choice of the use of various materials and production processes. The economical usage rate of all materials is a function of a number of variables. Some of the most important variables are the market price of some materials, notably various grades of steel scrap. This scrap price fluctuates, and therefore requires the periodic determination of economical usage rate. The work of Fabian (1958, 1967) is a cost minimization linear programming model that has four sub-models: one for iron making, one for steel making, and one each for shop loading for rolling operations and finishing operations. The models of various stages of production are connected to form a "Master Model" of an integrated steel plant. The detailed formulation at each stage and the principles of integration are also discussed in these papers. The model considers all the techno-economical constraints like the capacity balance, material balance, product-dependent yield and thermal energy balance (in the form of enthalpy balance). However, the oxygen balance and electrical energy balance are not discussed.

Large Scale Database Model for American Iron & Steel Institute

Fourer (1997) presents a model which grew out of a project to design an optimization package for steel mill planning. Because this project was supported by the American Iron and Steel Institute (AISI) and not any particular steel company, it was based on a generic model. Any steel plant could customize the model to its own operation, simply by supplying its own data. Users of this model would be concerned mainly with entering and maintaining their data and with reporting the optimal production levels. The model is generic in nature and can be transported to other similar industries like coal mining and oil refineries.

This work has been used in a number of steel plants such as LTV, Dofasco, and Armco. Dofasco has used this database optimization software to generate models in excess of 1000 variables and Armco has developed an equivalent of this software in a spreadsheet (Excel) using the same solver but with a variety of reports and diagrams customized to the company's requirements. In the LTV steel plant, it was suggested to use this model in two plant production and distribution problems.

On the basis of the above model, the importance of inventories and the linkage between the time periods was investigated by Hung (1991). Data for the plate mill and the batch annealing process at the Bethlehem, Armco, and LTV steel companies were used in an empirical study. In this study, the relations between the inventory level for plate mills and the batch annealing process were determined by least squares and least absolute deviation regressions. In addition, it was shown that production scheduling work can be accomplished in two steps: first assigning the slabs to each plate order, and then sequencing the rolling jobs. The slab assignment was formulated as a linear programming model with the objective of either maximizing yield, maximizing revenue or maximizing profit. Both the optimal slab assignment and the slab inventory are determined by the slab assignment model. The job sequencing problem then finds a job sequence that fulfills the operational constraints and also maximizes plate quality.

Models for Production Planning in the United Kingdom

Lawrence and Flowerdew (1963) develop an economic model of steel production with modeling focus on the application to the individual processes. A single cost model is constructed containing input and output variables, cost of variables and operations, relationships between and restrictions on the variables, technical relationships, and flow restrictions. A simplex type tableau is then constructed for a simplified model, and the optimal solution is then computed.

Bandyopadhay (1969) proposes a linear programming model that allocates different capacities between two processes for production planning, namely the Basic Oxygen Furnace and the Open Hearth Furnace. The model is a cost minimization model with all the technological and financial constraints. The model can also predict the required operation level of blast furnaces and lime burning plants at different levels of total steel production.

German Model at Hoesch Siederlandwerke

Bielfield, Walter and Wartman (1986) at Hoesch Siegerland Werke AG (HSW) in Germany have developed a set of accounting matrices for budgets for planning. The company had a revenue of one billion Deutsche Marks, and its main products were cold rolled, hot-dip galvanized, electro-galvanized, and organic coated sheet steel. The complexity of the steel company's structure and operation and rapid environmental changes forced the HSW management to replace a manual system with a computer-based strategic planning system having the objective of improving efficiency and performing mass calculations and cost accounting more efficiently. This is a linear programming model with the multiple objectives. These objectives may be maximizing revenue, minimizing total cost or cost per ton of steel produced. The model has about 2500 equations and 3000 structural variables.

Product-Mix Optimization Models in Indian Steel Plants

In India, the prices of half of all steel products were controlled by the Government from the fifties until 1991. In this environment, two interesting applications of planning have been reported.

During the past fifteen years, India has been affected by an energy shortage. The crisis is most significant in the eastern part of India where the gap between supply and demand is greatest. The poor capacity utilization of some power plants (which supply power to the steel plant) makes the operation of energy consuming plants extremely difficult. In the operation of a steel plant, some of the energy consuming processors (called essential loads) require a fixed amount of power and cannot be switched off, even in the event of power crisis. In this environment, the operating manager of a plant has no other option but to switch off those processors that are not essential loads. Optimal allocation of electrical energy is thus a very important decision for the management of the steel plant.

Dutta, Sinha and Roy (1990), Dutta *et al.* (1994) and Sinha *et al.* (1995) deal with the development and implementation of a mathematical model for optimal allocation of electrical energy in a steel plant. The guiding principle of the model is that in the case of a power shortage, power is allocated to those non-essential loads which have a higher profitability (based on a mixed integer linear programming model). Although a number of studies (Hunneault and Galiana, 1991; McCutcheon, 1988) have reported the optimal use of power plants, such studies have addressed the issue with a cost minimization modeling approach for power generating and distributing plants. Others have studied the most profitable use of an integrated steel plant (Fabian, 1958; Bielfield, Walter and Wartman, 1986; Baker *et al.* 1987) where the

In this case study, the steel plant has been modeled with a (contribution to) profit maximization objective, with energy as a limiting constraint. This is the pioneering attempt in India where the mathematical programming model has been implemented not only for long term strategic planning decisions, but also for short term operating decisions. This use is not only in an integrated steel plant, but also in an integrated steel plant vertically integrated with a tube manufacturing plant which requires higher complexity. The model considers all the technical and economical and environmental constraints such as the balance equation of capacity, material, energy and oxygen. It is an optimization model of an integrated steel plant with blast furnace, steel melting shop and primary and finishing mills in a global energy crisis environment or hot metal shortage situation. The model has different objectives: maximizing of contribution to profit, minimizing cost or maximizing production; it has about 1000 equations and 1000 variables. Its outputs are converted to a priority list of the facilities to be switched off during the energy crisis. The round-the-clock implementation of the model has improved the profitability of the steel plant significantly from 1986.

The Steel Authority of India Limited (SAIL), the largest steel company in India, is a multi-product company producing a wide range of products from its five integrated steel plants at Bhilai, Bokaro, Durgapur, Burnpur and Rourkella. The salable outputs from these plants can be divided into pig iron, semi-finished and finished steel. Another interesting option among these five steel plants is inter-plant transfers. This arises because of the imbalances at various stages of production across SAIL steel plants. Sharma and Sinha (1991) describe an optimization model for determining the optimal product mix for integrated steel plants of SAIL. The paper begins with a discussion of various issues relevant to the choice of an optimum product mix in a steelmaking operation. Some planned applications of the model are also discussed.

Models of Production Planning in Zambia

Sashidhar and Achray (1991a) have dealt with the problem of production planning in a steel mill with the objective of maximizing capacity utilization. The model has been formulated as a maximum flow problem in a multiple activity network. The production is usually planned against customer orders and different customers are assigned different priorities. The model takes into account the priorities assigned to the customers and also the order balance position. An algorithm is presented for solving the multiple activity network formulation for production planing with the customer priorities in a steel mill.

In another paper, Sashidhar and Achray (1991b) discuss the problem of allocating the major components of process costs to various quantities of products produced in a melting shop of an alloy and special steel manufacturing unit. Quadratic programming techniques are used to estimate the consumption pattern of important operational materials. These consumption patterns cannot be directly allocated to each quality of steel. Use of quadratic programming helps to arrive at more realistic and accurate route-wise and quality-wise costing at the melting shop.

Model of Production Planning in Algeria

Sarma (1995) describes an application of lexicographical goal programming at Societe Nationale de Siderurgie, Algeria. This is the only steel manufacturing plant at Algeria which caters to the domestic needs for steel production in several other industries such as railways, building, and bridge construction. Initially, an optimal solution is found which gives an indication of the optimal aspiration level of the management. The lexicographical approach has helped the management to spell out aspiration levels of several principal objectives such as profitability, capacity utilization of some key plants, and production quantity of some key products.

5. Blending Models

Generally, these problems are formulated as cost minimizing linear programming models. The thermo-chemical metallurgical processes in blast furnaces, coke ovens and iron and steel foundries are expressed as a set of constraints in a linear programming problem. The solution indicates a minimum cost selection of input materials in a production planning context. In addition to the plant or facility availability constraint, it considers the limitations of input and output materials. These limitations are given in the form of composition balance equations (such as carbon or sulfur balance) or as constraints on the basicity ratio (the ratio of lime to the sum of silica and alumina).

Blast Furnace/Cupola Blending Models in the United States

The blending of different ores or input charge materials in the blast furnace of a steel plant is known as a "blast furnace burdening problem." The results obtained from Fabian (1967) enable a producer to determine:

1. Least cost raw materials blending
2. Optimal furnace scheduling
3. Long range production planning
4. Optimal raw materials inventory levels
5. Optimal purchasing policies
6. Optimal maintenance planning

The cost minimizing output gives the solutions to the LP problem, the total cost of the burden, metallurgical analysis, heat balance report, burdening sheet, the marginal values of each resource, the reduced cost coefficients, parametric analysis in ranges, and availability of the facilities.

Metzger and Schwarzreck (1961) describe an application of linear programming for the determination of least cost cupola charging in an iron foundry. Their paper gives a numerical example with actual data, describes the evolution of the solution, discusses the difficulties overcome in developing the final version of the model, and summarizes cost savings.

Blending Model in the United Kingdom

Beale, Coen and Flowerdew (1965) propose a model in which the variables are usages, in a given time period, of ore and other materials, output of pig iron, and levels of certain factors that depend on the of mix of materials. In the real world, some of these models are nonlinear and a separable programming approach is useful. Representing each non-linear function of single variable as a piecewise-linear approximation based on a finite number of points, the problem can be solved by a slightly modified linear programming procedure. The same approach is repeated for nonlinear functions of more than one variable.

Blending Model in Belgium

This objective of this study, Hernandez and Proth (1982), was to save valuable metals whose supplies are uncertain and/or have to be imported. The problem of selecting the charge materials from available stocks in order to produce alloys as cheaply as possible is extremely important to foundries producing microcomponent alloys, such as bronze and special steel. The production of alloys at the lowest price from a number of stocks of scrap alloys of various composition and from unalloyed metals is achieved through the use of a new algorithm. The method differs from normal linear programming and avoids the shortcomings of known algorithms. The algorithm gives either an optimal solution or a "good" solution close to optimal. The system has been implemented to give an improvement in profit. In addition, the paper addresses the practical aspects of introducing this software.

Blending Model in Sweden

This work by Westerberg, Bjorklund and Hultman (1977) was done at Fagersta AB, Sweden and the Contact Research Group for Applied Mathematics, Royal Institute of Technology in Stockholm. The problem was modeled as a traditional blending model with the additional constraint that some of the variables should be integer valued. The Company produced stainless steel in HF (High Frequency) furnaces and used up to 15 different types of scrap and alloys which are melted together. The linear programming model is a cost minimization model with constraints of weight restrictions and metallurgical composition restrictions. The implementation of the model has decreased the cost of raw material by 5 percent which is equivalent to $200, 000 per year.

Blending Models in East European Countries

Muteanu and Rado (1960) solve a blending problem in a Rumanian steel plant that deals with the raw material loading of an iron-smelting furnace in such a way as to obtain an optimal production plan at minimum net cost of pig iron, taking into account definite prescribed production.

Another blending model by Taraber (1963) has been reported in Yugoslavia and this model has an objective of profit maximization. It provides an elementary example of the use of the linear programming and in deciding the composition of furnace charge for blast furnace.

6. Scheduling, Inventory and Distribution Models

In this section we discuss scheduling problems for continuous casters and hot strip mills, as well as problems of distribution, inventory, and optimal design of supply chains.

Scheduling Model at LTV Steel

In 1983, LTV Steel Company started up a twin strand continuous slab caster to convert molten steel to solid steel slabs. Located at LTV's Cleveland Works, the caster was scheduled by a computer-based system that included a heuristic algorithm developed by Box and Herbe (1988).

A casting sequence is required to meet all the operating and metallurgical constraints of sequencing slabs for production. The casting sequence also defines a sequence of heats - batches of molten steel - in which each 250-ton increment of the cast slab is of the same metallurgical grade. The problem of sequencing slabs from the requisitions on a single strand of a caster is similar to a knapsack problem, where the most important orders from the order book are given the greatest value.

The complexity of the problem increases for a twin strand caster, which produces two simultaneous and independent production streams from one source of molten steel. The problem becomes like a routing problem for two knapsack constrained traveling salesmen, traveling on two interdependent itineraries. The "pool" of cities is available to both salesmen, but their paths are mutually exclusive because a slab for a requisite order can be produced only once. Further the two salesmen must arrive at certain cities at the same time because of constraints imposed by successive heats. Both production streams begin with the same heat, and the sequence ends when the last heat is consumed. Thus the sequence must end on both strands at roughly the same time.

The caster scheduling model determines the requisitions that are to be filled in a sequence of heats, the order of slabs produced in the sequence and the nature of heats needed to produce the specified slabs in the specified sequence. A heuristic is used since the combined problem (synchronizing, sequencing and assignment) is very complex and some of the constraints are difficult to state mathematically in a form suitable for inclusion in mathematical programming formulations. The objective function is pseudo-cost per ton for producing a given cast sequence. It is not the total cost, but rather the relative savings of continuous casting compared to teeming (that is, casting by pouring molten steel into molds). This system annually saves over $1.95 million by reducing personnel and increasing production. Also, using the schedules determined, the design capacity of the caster has been surpassed by 50 percent.

Scheduling Models at Bethlehem Steel

In the late seventies, Bethlehem steel needed 4000-6000 cast iron and steel rolls every year to manufacture product of various shapes in its 100 mills located throughout the U.S.A.. The rolls are first cast at foundries and then machined in a large generalized machine shop with 35 machines. In this context, Jain, Stott and Vasold (1978) developed and implemented an order book balancing procedure with a combination of linear programming and heuristics for improvement in order book balancing when demand exceeds supply. The objective function of the linear program is to maximize the total tonnage of rolls produced subject to machine availability and supply and demand constraints. The implementation of the model has improved efficiency and customer service, reduced work-in-process inventories and machine setup time, and improved due date performance.

Stott and Douglas (1981) describe a scheduling system for ocean-going vessels that are employed in shipping raw materials from around the world to Bethlehem's plants. There are four subsystems encompassing a range of time scales: Voyage Estimation, Preferential Employment, Single Vessel Scheduling, and Multiple Vessel Scheduling. At the time of publication, this system had been running for more than 4 years and had resulted in several tangible and intangible benefits and had led to a number of spin-off projects.

A significant portion of scheduling and sequencing problems in the steel industry can be formulated as zero-one integer programming problems. Typically these applications cannot be solved using an exact branch and bound approach. Vasko *et al.* (1993a) discuss an intuitive user controlled variable tolerance approach to depth-first branch-and-bound algorithms. Several scenarios of a specific real-world example problem illustrate how the parameters in the variable tolerance approach have an impact on the solution quality and execution time.

The optimal design of production through a hot strip mill is characterized by multiple and conflicting objectives. Jacobs, Wright and Cobb (1988) propose an optimization model for this situation. Considering the hot strip mill as an isolated facility, a "just in time" delivery scenario is modeled as a goal program. A case study of the Burns Harbor Plant is reported.

Newhart, Stott and Vasko (1993) approach the optimal design of the supply chain in two phases, using a mathematical programming formulation and a spreadsheet model. First the mathematical programming and heuristic solution approach are used to minimize the distinct number of product types held at different points in the supply chain. Then a spreadsheet model is used to estimate the safety stock needed to absorb the random fluctuations in both demand and the lead time throughout the system. The implementation of this two-phase approach allowed management of Bethlehem Steel to quantify the effect of inventory required for locating parts of the supply chain in different geographical areas. This study was a critical factor used by top management to clarify a final decision-making process.

Optimal assignment of structural steel shapes to rail cars is an important logistics problem in the steel industry. Vasko *et al.* (1994) discuss an application that incorporates weight, dimension and customer loading constraints. The formulation is a generalized bin-packing problem which is solved by modifying and extending previous algorithms. It has been used extensively for one of the Bethlehem's high tonnage customers, providing very good practical and implementable results that achieve the desired goals.

Vonderembse and Haessler (1982) present an effective algorithm for combining customer order sizes so as to economically schedule the longitudinal ripping of cast slabs. This solution process can assist decision makers in selecting master slab widths and in designing width limitations for future casters. It entails more than the minimization of trim loss, because other costs are relevant. This procedure has been successfully used by the production control department.

Inventory Model for AISI

On the basis of the steel product-mix optimization model discussed by Fourer (1997), the importance of inventories and the linkage between the time periods was investigated by Hung (1991). Data for the plate mill and the batch annealing process of Bethlehem, Armco and LTV were used in an empirical study, sponsored by the American Iron and Steel Institute. Relations between the inventory level for plate mills and the batch annealing process were determined by least squares and least absolute deviation regressions.

A two-step procedure for production scheduling was also proposed. It first assigns slabs to each plate order and then sequences the rolling jobs. The slab assignment was formulated as a linear programming model with the objective of either maximizing yield, maximizing revenue or maximizing profit. Both the optimal slab assignment and the slab inventory mix are determined by the slab assignment model. The job sequencing problem then finds a job sequence that fulfills the operational constraints and also maximizes plate quality.

Dynamic Scheduling at Ensidesa Steel in Spain

After building a new steel plant, Empresa National Siderurgica implemented automatic control in various production sections, giving the process computers continuous and complete information throughout the production process. Making use of this information, Diaz *et al.* (1991) developed an automatic coordinating system for each facility in the plant. In this system, the operator selects a set of heats to produce and makes a predetermined production scheme from various pre-planned strategies. The system then arranges the heats accordingly and simulates the delay and the idle times that could occur if the operator chooses that scheme. Unlike some American steel plants (where the sequences last for dozens of heats) the Spanish steel plants have short sequences (six or seven sequences per day). As the sequences are short, the objective is to maximize the time the casters are producing slabs.

Scheduling Model at a Canadian Steel Plant

This work by Boukas, Haurie and Soumis (1990) is a model of optimization of productivity in a steel plant subject to global energy constraints. The plant had four arc furnaces and three continuous casting machines. In electric arc furnaces, the allocation of energy, the fusion phase of the total production cycle, is of critical importance. The problem is to define the start time and the duration of a production cycle in combination with a power schedule which meets the energy requirements of the different furnaces and a global power supply limit for the whole plant. The problem is formulated as a combination of an optimization problem and an optimal control problem. The authors have proposed a two-level algorithm which shows nine percent improvement in productivity on some test data.

7. Set Covering Applications

In this section, we discuss applications of the set covering approach in the area of assignment of slabs to orders, metallurgical grade assignment, and selecting optimal ingot sizes. All studies in this section have been reported at facilities of Bethlehem Steel.

Optimal Ingot Size Determination

After installation of a new ingot mold striping facility in 1984, Bethlehem Steel developed a two-phase procedure for selecting optimal ingot dimensions, as reported in a series of publications (Vasko *et al.*, 1989a; Vasko and Wolf, 1988; Vasko, Wolf and Stott, 1987; Vasko and Wilson, 1986; Vasko and Wilson, 1984a; Vasko and Wilson, 1984b; Vasko, 1984). Previously, Bethlehem had been using about a dozen ingot mold sizes. Based on experience it was established that any increase in the number of distinct mold sizes would result in a significant increase in inventory and material handling cost.

The two-phase procedure is used for selecting the optimal ingot dimensions and internal mold dimensions. This procedure also incorporates research in yield improvement and a variety of metallurgical and operational constraints. Only marginal improvement would have been possible if the old mold sizes had been retained. Phase I of the procedure generates feasible ingot mold dimensions consistent with the constraints; Phase II then uses a set covering approach to select, from the feasible sizes generated, the ingot dimensions and ingot mold dimensions that minimize the number of distinct mold sizes required to produce the finished products. On the basis of the results of this model and trial mill tests, full production use of new mold sizes influenced the entire plant operation and resulted in annual savings of over $8 million.

Metallurgical Grade Assignment

Another application of the Phase II method mentioned above is a metallurgical grade assignment model by Vasko *et al.* (1989b). The installation of a continuous caster required an accompanying production planning and control system. This module, responsible for assigning metallurgical grades to customer orders, uses a minimum cardinality set covering approach that not only minimizes the number of metallurgical grades (required to satisfy a given collection of customer orders), but also a preference to priority orders. The algorithm is used in a two-pass mode to quickly generate very good solutions to these large scale (up to 1000 zero-one variables and 2500 constraints) optimization problems. When compared to the traditional method, this method had a potential to significantly improve caster productivity.

Later papers (Woodyatt *et. al.*, 1992; Woodyatt *et al.*, 1993) have discussed the limitations of the above method and have suggested a combination of set covering and fuzzy set methods. In order to use this approach to assign metallurgical grades to a collection of customer orders, metallurgists must first specify the set of all grades that satisfy the requirements and specifications of those orders. However, the set of all metallurgical grades that meet a customer's requirements is not well defined. In their paper, the authors have discussed a methodology where each customer order defines a fuzzy subset of the set of all metallurgical grades. They have also defined a membership function that is based on the likelihood of the grade meeting the customer specifications. The methodology addresses the tradeoff between minimizing the number of grades used to produce a collection of customer orders versus maximizing the likelihood that customer specifications will be met.

Assigning Slabs to Orders

Another important problem in the steel industry is the assignment of semi-finished slabs to orders. Instances may be too large (12000 to 16000 zero-one integer variables) to be solved in a reasonable amount of computer time. Vasko *et al.* (1994) have described a transportation formulation of the problem that can be solved using a network optimization code. Then, using rounding heuristics, the result can be used to provide a practical solution. The methodology, formulations and algorithms are generic and can be used to solve a large variety of set covering applications in steel and other industries.

8. Cutting Stock Problems

As reported by Tokuyama and Nomuyuki (1981) of Sumitomo Metal Industries, Japan, the characteristics of the cutting stock problems in the iron and steel industries are as follows:

- There are a variety of criteria such as maximizing yield and increasing efficiency.
- Cutting problems are usually accompanied by inventory stocking problems.

Practical algorithms that give near optimal solutions in the real world have been developed. In their paper, Tokuyama and Nomuyuki discuss applications to one dimensional cutting of large sections and two dimensional cutting of plates. The following other applications have also been reported.

Cutting Stock Optimization in American Steel Plants

In a continuous caster, master slabs are produced that are wider than the rolling mill can process. Haessler and Vonderembse (1979) describe the master slab cutting stock problem and present a linear programming based procedure for solving it. A primary objective in solving the problem is to fill as many orders as possible without generating any loss. This is realistic as the cut slab can be spread and squeezed at the known limits at the rolling mills to obtain the desired coil length. An example is presented and solved.

In a plate mill, surplus rectangular plates (flat pieces of steel used in production of railroad cars, ships, and boilers) of nonstandard dimensions are generated as by-products of the batch steel making process. An important implementation of the two dimensional cutting stock problem is the application of customer plate orders directly to the surplus steel plates. Although high yield cutting patterns for surplus plates are very desirable, the following other considerations are also important:

1. Cutting few orders from each surplus plate (productivity reasons).
2. Cutting most of the high priority orders from the plates (customer service considerations)
3. Cutting orders from a plate for as few distinct customers as possible (logistical concerns).

Vasko, Wolf and Stott (1989) and Vasko (1989) present a formulation in a fuzzy environment that addresses these concerns. A solution procedure is outlined and practical implementation at Bethlehem Steel's Sparrows Point Plant is described in Vasko, Wolf and Pflugrad (1991). The plant can produce narrow width customer-plate orders (typically 10 to 24 inches) efficiently when its 60 inch plate mill is not operating. The heuristic procedure is used to map these orders into mother plates for production in the 160 inch plate mill. This procedure was implemented as a module in the plant's production planning and control system and has been used daily to generate mother plate dimensions and cutting patterns.

In another application, Vasko *et al.* (1992) discuss a method that combines set covering and cutting stock applications for improving Bethlehem Steel's customer service. Some of the customer orders are slit from master coils into a number of narrower and smaller coils to fit specific manufacturing needs. To serve these customers, Bethlehem has developed a mathematical model that generates optimal coil widths and slitting patterns. The model has the following objectives:

1. Minimize the number of slitter setups
2. Maximize the material utilization
3. Generate minimum excess inventory
4. Generate minimum shortfall against forecast demand

The linear program also generates coil widths that optimally utilize the company's facilities. This system is viewed by the customers as a value added service provided by Bethlehem Steel.

Vasko and Wolf (1994) address the problem of determining what rectangular sizes should be stocked in order to satisfy a bill of materials composed of smaller rectangles. They first generate a large number of stock sizes ideally suited to the bill of materials; then they use an uncapacitated facility location algorithm to consolidate the stock sizes down to an acceptable number. Once the solution of finding rectangular stock sizes is known, a second program is used to map the bill of materials onto plates of the chosen sizes. The practicality of the approach is demonstrated by generating a cutting plan for a real world bill of materials having 392 distinct order sizes and over 7700 order pieces.

In a mill finishing a structural shape such as an I-beam, once the final product is produced, it is cut according to the customer's order length. The actual length may not be known precisely until just before cutting. Also if the production rate of the mill is higher than the cutting rate of the bars, then trying to generate cutting patterns with the number of cuts per bar close to the average number of cuts per bar will maximize primary saw (hotsaw) cutting and reduce the number of cuts that have to be made at the secondary saw (coldsaw). Vasko *et al.* (1993b) discuss a branch-and-bound algorithm that generates high yield, balanced cutting in real time based on the precise length of the bar leaving the mill and arriving at the saw.

Cutting Stock Applications in a German Steel Plant

Pohl and Kaiser (1982) develop a cut length optimization program for the computer controlled Siege GeisWeid AG rolling mill. They describe a procedure for cutting the rolling strand lengths into marketable lengths. The total rolling strand length is computed by comparison of volume and speed of billets, merchant bars (after the first rolling block), and finished products. The speeds and lengths are determined by measuring rollers in the front part and without contact at the rear end of the mill. The cooling bed lengths are divided according to the optimization computation and are conveyed under computer control to two cutting-off machines, which cut into marketable finished lengths.

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9. Other Applications

The continuous casting machine can be used to eliminate a number of processing steps associated with the traditional ingot/bloom based production sequence. However, a given continuous caster can produce only a small number of bloom thicknesses. This creates a problem for selecting those continuous-caster configurations that would maximize utilization. Vasko and Friedel (1982) present a dynamic programming formulation that maximizes the cast bloom tonnage that can be processed through one of the Bethlehem Steel's finishing mills. Without the aid of such a model, selecting the highest productivity would have two conflicting considerations. The first factor is that as the number of caster-produced bloom thicknesses increases, the caster setup time and the configuration complexity increases. The second factor is that as the number of thicknesses decrease, the cast tonnage processed through the finishing mill is reduced, owing to reheating furnace and cooling bed limitations. The model results were transmitted to the plant management and were used in conjunction with other information to determine the most economic caster configurations.

The Electro-Slag Remelting (ESR) process was developed for melting special alloys that were difficult to produce in conventional electrical arc furnaces. Gower, Hahn and Tarby (1970) describe an application of dynamic programming simulation to determine an ESR operating policy that is predicted to maximize cumulative profit over a number of stages.

10. Conclusion and Extensions

Although steel is a basic industry for the growth of a nation, relatively few applications of mathematical programming have been reported in comparison with other industries such as oil, airlines, and semiconductors. Also, very little work has been done in the area of inventory control and manufacturing control for steel plants. However, it is noteworthy that four applications (Jain, Stott and Vasold, 1978; Box and Herbe, 1988; Vasko *et al.*, 1989a; and Sinha *et al.*, 1995) have been selected as finalists in the Management Science Achievement Award (Edelman Competition). This gives an indication of the potential financial benefit of applying optimization techniques to the problems of the steel industry.

From the survey of different applications and our personal experience in the modeling of steel plants, the following can be considered as potential areas for future work:

1. Simultaneous optimization of product-mix, inventory and transportation problems over multiple periods. This would represent an extension of Fabian (1958) to the multi-period case with inventory and transportation requirements as additional constraints.

2. Cutting stock optimization to maximize overall yield of multi-stage production processes. This would go beyond most previous work on the cutting stock problem, which has used single stage models.

3. Scheduling problems in the continuous caster.

4. Stochastic linear programming models where not only the means and variances of the stochastic entities but also their distributions are known.

5. Any research that increases the reliability and validity of the data. The success of mathematical programming models depends heavily on availability of relevant data. Often the desired data does not exist, or must be collected from multiple sources.

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