Chapter 10
Applications of Mathematical Programming Models for Product Mix Optimization in World Steel Industry: Challenges and Directions

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Abstract The world steel demand by construction industry, mechanical engineering industry, and metal goods industry is more than 78 %. More than 46 % steel is supplied by China, while India's steel supply share is approximately 5 %. The production of world crude steel increased from 851 megatons (Mt) in 2001 to 1,548 Mt in the year 2012. Also, world average steel use per capita has increased from 150 kg in 2001 to 215 kg in 2011.

Mathematical programming models for product mix optimization have been applied to various industrial sectors to achieve improved performance. Process industry, especially the steel sector, has been home to extensive mathematical programming applications. In this paper we present a survey of more than 20 reported publications in the field of mathematical modeling to determine optimum product mix in an integrated steel plant. It suggests a classification of models based on the functional areas they are applied in. The study is an attempt to review the mathematical programming application in product mix optimization in integrated steel plants. The study summarizes the various applications of genetic algorithm, revenue management, energy modeling, and modeling uncertainty in the model parameters.

The study concludes that there is a growing need of modeling uncertainty in demand and prices of finished goods of steel. The future researchers should also focus on modeling multiple objective mathematical models, genetic algorithm, and revenue management application. The alternative interesting extensions are to explore if the similar applications exist in other metal processing industries, viz., aluminum, copper, etc. The mathematical applications in one industry have significant scope to replicate in other similar process industries. The study states that the current paper has reviewed reported literature from product mix optimization real-world applications. This is an interesting extension of this research to review the reported literature from multiple areas including cutting stock, financial planning, blending, implementation of decision support systems, production and capacity planning, etc.

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1 An Overview of Steel Production Process

In a steelmaking plant, the first stage is iron-making stage in which iron ore is converted into molten iron in a blast furnace. This molten iron is then converted into molten steel by any of the methods such as basic oxygen furnace or open-hearth furnace:

$$Fe_2O_3 + 3CO \rightarrow 2Fe + 3CO_2\ \Delta H = -22\ \text{kJmol}^{-1}$$

$$Fe_3O4 + 4CO \rightarrow 3Fe + 4CO_2\ \Delta H = -10\ \text{kJ mol}^{-1}$$

The molten steel is then cast in a continuous caster into ingots and rolled into blooms and slabs, which are then rolled into strip bars, sheet bars, or billets. These are converted into ordinary strips by strip mill and shipped to market or a tube making plant.

2 World Steel Industry

The production of world crude steel increased from 851 megatons (Mt) in 2001 to 1,548 Mt in the year 2012 (refer to Fig. 10.1). Also, world average steel use per capita has increased from 150 kg in 2001 to 215 kg in 2011 (World Crude Steel Production 2012).

China is the leading producer of steel in the world (refer to Fig. 10.2). India, Brazil, Turkey, and South Korea have all entered the top ten steel producers list in the past 40 years.

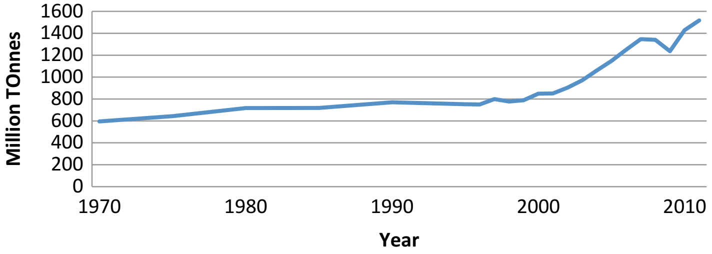

Fig. 10.1 World crude steel production 2012 (Source of Data: World Steel Association)

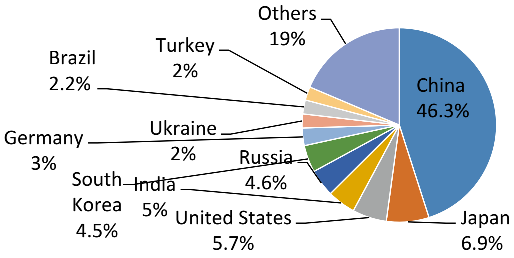

Fig. 10.2 Major steel producing countries 2012 (Source of Data: World Steel Association)

The use of steel can be seen in almost every aspect of our lives. It has a unique combination of strength, formability, and versatility. Almost 200 billion steel cans for food storage are produced each year, which means cutting down on energy usage refrigeration is not needed anymore then.

Steel used for double-hulled cape size vessels which are used to deliver raw materials, finished goods, and energy must have the highest impact toughness, corrosion resistance, and weldability. Skyscrapers have been made possible only by steel. The housing and construction sector is the largest consumer of steel today, it uses around 50 % of world steel production. Approximately 25 % of an average computer is made of steel. In 2010, more than 320 million PCs were sold. Also, steel surfaces are hygienic and easy to clean; therefore, all surgical and safety equipment and commercial kitchens are made with steel.

3 Product Mix Optimization

In an integrated steel plant, it is very important to determine the optimum production level at various stages of steel production. Profit does not depend solely on the volume of the production but also on product mix produced. Suboptimal solutions are obtained by practitioners by experience. However, the profits generated by implementing these solutions are way less than the potential profit that could have been made using the optimum product mix. The optimum product mix depends on the availability of mill or furnace and demands for the product, and it keeps changing from 1 month to another.

4 Mathematical Programming Applications in Steel Industry

Steel is produced through a continuous production process where it is impossible to decompose the product into its constituents. Also, once the production starts, it is not economical to shut down production. The continuous production process, and therefore, steel production, is highly capital intensive and the production process is very complex. Most steel plants are integrated as a variety of products move through different series of production units. Finished products are produced in different shapes and sizes. The production process also takes place under high-temperature and high-weight material flow and incorporates complicated technology. The various equipment are designed for a specific capacity. The demands for various types of finished products are different and have to be produced using the same set of equipment. Under such situations, characterized by technological, material, capital, environmental, and energy constraints, it becomes imperative for production managers to utilize the various resources optimally so as to achieve the desired production targets. If wrong decisions are taken, it will result in losses. Therefore, it presents the right situation to use mathematical tools to achieve optimum levels of production while making effective and efficient utilization of various kinds of resources.

5 Linear Optimization

Fabian (1958) presents a cost-minimization linear programming model. It has four sub-models, one for each stage of iron making, steelmaking, and shop loading for the rolling operations and finishing operations. An integrated steel plant generally has a choice to select among different materials and production processes. There are variables on which the economical usage rate of different materials depends, for example, the market price of various grades of the steel scrap. The price keeps fluctuating, and therefore a periodic determination of the economical usage rate is important. In the paper, the models of different stages of production are then connected to form a "master model" in an integrated steel plant. The author has also discussed the detailed formulation of the model at each stage and then the principles of integration. Most of the technical and economic constraints like the material balance, capacity balance, thermal energy balance, and product-dependent yield have been considered.

Fabian (1967) explores an application of linear programming with multiple objectives in blast furnace production planning. The blast furnace production process is described in detail, and in the linear programming problem, the thermo-chemical metallurgical process is stated as a set of constraints.

Bandyopadhyay (1969) proposes a cost-minimization linear programming model for capacity allocation in production planning. In an integrated steel plant where both basic oxygen and open-hearth furnaces are available, it is a general problem of optimal allocation of steel production between the two of them. The model incorporates all the technological and cost constraints.

Tsao and Day (1971) present a process analysis model of steel production in the United States. A technology matrix, which represents recent technology structure in terms of input and output, is estimated by using engineering and metallurgical information. Then this matrix along with the detailed data on cost, sales, revenue figures, and resource capacity is used in a linear programming model to make short-run allocations in the whole of the steel industry. Once the model's solution is obtained, it is compared with actual industry statistics for each year from 1955 to 1968. The authors claim to have fairly good results; however, Nelson (1971) commented that there was an error in the treatment of the coking coal production. He attempted to correct this problem and developed a correlated matrix for this particular stage of production.

Sharma and Sinha (1991) present an optimization model with the objective of determining the optimal product mix during production planning for the integrated steel plants of Steel Authority of India Limited. In the paper, various issues related to the choice of an optimum product mix in the context of a steelmaking operation are discussed.

Sasidhar and Achary (1991) develop a model in the form of a maximum flow problem during production in a multiple-activity network. The objective is to maximize capacity utilization. The production at a steel plant is generally planned according to the customer orders, so different customers are therefore assigned different priorities. The model deals with these priorities assigned to the customers and the balance of orders. The authors present an algorithm to solve the multiple-activity network formulation with the customer priorities in a steel plant.

The linear programming models developed in the context of steel production are useful for allocation of steel production in different processes, allocation of the key input materials for production, analyzing industry problems such as resource utilization and economies and diseconomies related with selection of input mixes, and optimum utilization of sequence capacities.

6 Advanced Linear Programming Applications

Lawrence and Flowerdew (1963) present a single-cost model for steel production that contained a number of input-output variables, technical relationships between them, their cost and operations, and flow restrictions on them. Then a simplex-type representation is made, and thereafter optimal solution is calculated.

Mohanty et al. (2003) describe a genetic algorithm (GA)-based method of assortment in steel industry to determine the optimum width of the parent stock so that the trim loss is minimized. The study evaluated six selection techniques for the selections of parents and concluded that elitism selection technique gives the best results. The authors suggest that for future research advanced GA operators or other techniques such as dynamic programming can be used for solving the assortment problem.

A column generation algorithm is proposed by Song (2009) to solve the problem of allocation of orders to stock materials in surplus inventory in steel mills. It is called multistage multiple knapsack problem; in the first stage of the problem, slabs are designed using orders with similar properties and in this stage these designed slabs are allocated into the existing meta slabs in the inventory yard. The proposed algorithm solved the real instances in reasonable time, when it was tested in an integrated steel company and has been successfully deployed to other integrated steel mills. It has released human planners from the cumbersome tasks of daily allocation which contains at least a few hundred materials in the stockyard. It is also mentioned that complex multi-objective function and the design of two-dimensional mother plates explained in the paper are good avenues for future research.

As'ad and Demirli (2011) develop a bilinear programming model and a branch-and-bound-algorithm-based method for production planning in steel rolling mills with a substitutable demand. They address the dynamic capacitated multi-item lot-sizing problem, abbreviated as CMILSP, which is encountered typically in the steel rolling mills. The various end items' lot sizes are determined at the master production schedule level to minimize the total cost. Then the production-inventory problem is formulated as a mixed-integer bilinear program (MIBLP) under various technological constraints. The authors have also used an alternative branch-and-bound algorithm for solving the problem that is benchmarked against the linear optimization techniques.

Kwak et al. (2010) proposed a procedure called Patient Rule Induction Method for optimization of a multistage manufacturing process. It is important to take into consideration the relationship between the stages of a multistage manufacturing process, in order to optimize it. The PRIM can extend the scope of process optimization from single-stage process to multistage process and also use the information captured in relationship between the stages, while maximizing the performance of a stage. It is mentioned that PRIM can be used when a sufficiently large set of operational data is available. It may be interesting to explore that the use of PRIM to optimize the multistage manufacturing process when small data is available is the key issue of future research. Apart from steelmaking, its scope also extends to automotive industry, LCD, semiconductor, etc.

A number of problems such as assortment problems, optimizing multistage manufacturing process, and solving the given test instances within reasonable time have been addressed by advanced linear programming. Such problems are difficult to model as linear systems. Solutions are generated by genetic algorithms, mathematical programming coupled with linear programming, column generation algorithms, etc.

7 Financial Planning Applications

Kendrick et al. (1984) propose three models in all —two static ones for production planning and one dynamic one for investment analysis. The two static models, expressed as linear programming models, are transportation and mixed production problems. The inputs in the model are prices of raw materials, facility capacities, operations and shipments, demands, and input and output coefficients for each productive unit. The outputs are optimal product distributions. On the other hand, the dynamic model is a mixed-integer program that incorporates time factors and also deals with the issues of investment in five time periods— each of 3 years. In both models, the inputs are similar; however, the output in the dynamic model also includes investment decisions.

Bielfield et al. (1986) at a steel company Hoesch Siegerlandwerke AG (HSW) in Germany developed a set of accounting matrices for the purpose of budget planning.

The company main products were hot-dip galvanized, cold-rolled, electrogalvanized, and organic coated sheet steel, and it had a revenue of about one billion Deutsche Marks. The issue of complexity of the company's structure, its operations, and the rapid environmental changes pushed the management at HSW to replace the manual system with a computer-based system for strategic planning with the objective to improve efficiency and perform mass calculations and cost accounting with better efficiency. The authors presented a linear programming model with 3,000 structural variables and 2,500 constraints. It has multiple objectives of maximizing revenue and minimizing total cost.

Another paper by Sashidhar and Achray (1991) discusses the problem of allocation of the major components of the process costs to different quantities of products that are produced in the melting shop of an alloy and in a steel manufacturing unit. The authors have used quadratic programming techniques to estimate the pattern of consumption of important operational materials. However, these patterns cannot be directly assigned to each quality of steel. Here, the quadratic programming helps to arrive at more accurate and costing both route wise and quality wise.

Hintches et al. (2010) presented an application of revenue management (RM) technique to maximize profit in a made-to-order (MTO) scenario by selecting the best orders. In an MTO scenario, it is not the product that perishes but the capacity. Application of RM involves assessment of opportunity cost of an order to determine whether the order needs to be accepted or not. The authors had demonstrated by using a case study of capacity control at ThyssenKrupp VDM using RM techniques, and it was found that there was a substantial difference in profit margin.

Chauhan et al. (2012) aim to find an optimum product mix in cold rolling steel industry (JSW) which is a leading cold rolling and galvanizing house in India. The monthly production of the company is 45,000 mt, and it aims for maximum EBIDTA and for maximum utilization of the whole main line. Thirteen products have been selected for optimization, and the company aims to decide the monthly production in tonnage for each selected product. For this a product-portfolio matrix is formed that shows which products are more convenient to produce considering market attractiveness. A multiobjective linear programming model is applied for getting optimal product mix solution. The results so obtained are then compared with the actual figures of the company, and then the final production figures of all the 13 products are frozen for maximum EBIDTA and for maximum utilization of plant.

The investment decisions in steel plants have to be taken in uncertain environment. The volatility of steel prices and demand variability can alter the economic performance of the projects. In integrated steel plants, the blast furnace has to remain working continuously; therefore, production cannot be lessened or interrupted in between. In this scenario, simulations and modeling of uncertainties are of great value.

A number of attempts have been made by using mathematical modeling techniques to optimize the product mix and generate maximum revenue or EBIDTA or maximum utilization of an integrated steel plant. Future research can be conducted to find methods of updating forecast and resulting re-optimization. The area of dynamic bid prices can be explored.

8 Energy Modeling

Dutta et al. (1994) develop a mathematical model for optimal allocation of electrical energy in a Tata Steel plant in India. There is persistent problem of adequate power supply in India, due to which at times of power shortage, it is important that power be allocated to such nonessential loads that yield higher profitability. The steel plant was modeled with the objective of profit maximization and taking energy as a limiting constraint. Sinha et al. (1995) also developed a mixed-integer linear programming model for Tata Steel to optimize their operations amidst scarce resources. Earlier study by Hunneault and Galiana (1991) that looked into optimal use of power addressed this issue with cost-minimization modeling approach. Some authors have addressed the problem as a profit-maximization linear programming model. The model developed in India is also useful for making short-term operating decisions. It considers all economical, technical, and environmental constraints such as materials, energy, balance of capacity, etc. It is an optimization model with multiple objectives of minimizing cost, maximizing profit, and maximizing production and has about a thousand variables and a thousand constraints. The output obtained is a list of facilities that should be switched off during the energy shortage.

The problem of power shortage is taken care of by energy models that provide solutions to prioritize in case of power crisis, to plan the production target, and to devise a marketing strategy situations that arise due to failure of blast furnaces, oxygen plant, shortage of scrap, etc. These models can be used in other similar industries too because the problem of power shortage runs throughout countries like India.

9 Modeling Uncertainty

Dutta and Fourer (2004) describe a generic multi-period optimization-based decision support system (DSS) that can be used for strategic and operational planning in process industries. The DSS built on the five fundamental elements – materials, activities, time periods, facilities, and storage areas – requires little knowledge of optimization techniques to be used effectively. The results are based on real data from an American integrated steel company and they demonstrate significant potential for improvement in revenues and margins.

Denton and Gupta (2004) had proposed a two-stage stochastic integer programming model for planned inventory deployment that can be used to choose the semifinished products that should be made to stock and their target inventory levels. Thus, strategically placing the semifinished inventory into finished products would help integrated steel manufactures, characterized by high capital expenditures and long cycle time, to reduce the time between receipt of order and dispatch of the order and its variability. Also, they mention that the model is applicable to problems involving the configuration of transportation networks in a scenario of demand–supply uncertainty. In the future, modifications in the model can be made to account for more factors which were not considered in this study, other factors such as capacity constraints on total production or randomness in second-stage cost coefficients.

Ozorio et al. (2013) used Monte Carlo simulation to calculate the value of a product exchange option in a steel mill that has a blast furnace with a hot roller. Since the demand is uncertain, in steel mills, it is a common practice to invest in steel rolling assets, so that production can be diversified and product exchange options can be generated. In the study it was found that this option can yield a significant increase on the net present value (NPV) of a blast furnace steelmaking projects (exact value of NPV difference can be looked up) and also that it makes a difference as to which type of stochastic process is used to determine the option's value. The authors used two different types of stochastic processes, the regression-to-the-mean reversion movement (MRM) and the geometric Brownian motion (GBM) in their study. The interested readers are encouraged to refer to Ozorio et al. (2013) for the mentioned stochastic processes in detail.

10 Conclusion and Extensions

This paper presents a guide to the optimum product mix in an integrated steel plant and dispatching literature from the late 1950s to present. The mathematical models are classified according to different techniques used, and the functional and chronological order and relationships are shown. We conclude that there is marked progression in the mathematical modeling of product mix optimization that can be seen in the steel industry across the world.

From the survey of different applications in the modeling of the steel plants, we believe that the following can be some potential areas for future work:

1. Developing models in a rolling horizon context to account for uncertainties associated with production capacity and demand
2. Complex multiple objective function to address a number of problems simultaneously
3. A systematic framework to update and re-optimize in a made-to-order network setting
4. Dynamic programming to solve assortment problem
5. Application of advanced genetic algorithm operators solving problems in integrated steel plants

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