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Modeling and optimization methods of integrated production planning for steel plate mill with flexible customization☆

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ABSTRACT

With diversified requirements and varying manufacturing environments, the optimal production planning for a steel mill becomes more flexible and complicated. The flexibility provides operators with auxiliary requirements through an implementable integrated production planning. In this paper, a mixed-integer nonlinear programming (MINLP) model is proposed for the optimal planning that incorporates various manufacturing constraints and flexibility in a steel plate mill. Furthermore, two solution strategies are developed to overcome the weakness in solving the MINLP problem directly. The first one is to transform the original MINLP formulation to an approximate mixed integer linear programming using a classic linearization method. The second one is to decompose the original model using a branch-and-bound based iterative method. Computational experiments on various instances are presented in terms of the effectiveness and applicability. The result shows that the second method performs better in computational efforts and solution accuracy.

1. Introduction

During the past few years, severe market competition and stringent customer requirements have directed decision makers' attention to the development of a more efficient production management strategy. The iron and steel industries, for instance, have encountered the predicament of reduced revenues and increased costs, due to the rising price of raw materials and rigorous product quality [1]. For an operation manager, one of the viable tools is to improve and implement production planning and scheduling technologies specific to steel mill requirements and customer focuses.

With increasing demand for steel products and extending production scale, production planning in a steel mill plant is becoming more complex. Moreover, the delivery way is variable and customers need flexibility in product specifications [2]. Since steel products differ in dimensions and alloys, 'downward substitution' often exists in practice, where the demand of a certain product can be fulfilled by a similar one with the same dimensions but higher quality or with the same quality but larger dimensions through cutting and pruning. On the other hand, varying manufacturing conditions complicate the operation and decision-making. For example, large steel mill plants usually build more than one rolling mill and each product can be rolled by more than one raw materials. Consequently, effective planning in a large and complex steel mill industry is not easy. Decision-makers must consider both the production and inventory status, and handle these flexible operations. However, in most cases, with vast production scales, decision-makers rely highly on their experience and select a certain feasible solution, other than the optimal. Under these conditions, a systematic approach is required to design a flexible steel mill planning system, operating economically and steadily.

The steel mill considered in this paper produces steel plates, with steel slabs as the raw materials differing in dimensions and alloys. A large-scale complex optimization model is formulated and solved to provide optimal production and operation strategies and flexible options. For large manufacturing enterprises, production planning encompasses three levels for decision-making: planning, execution and operations [3]. The integrated production planning problem focuses on the executive level, where customer requirements are executed by determining production route and lot sizes over the planning horizon, while the planning for capacity and raw material requirements is incorporated. Usually, production capacity requirements and material requirements are the inputs and outputs, respectively, where available capacity is given roughly upon the production quantity on operators' experience [4]. Nevertheless, since the raw materials for steel plates are produced and restricted by the upstream casting stage, material requirements would be tackled as the feedback input. Giving production capacity requirements based on experience may result in utilization imbalance, so the capacity restriction should be relaxed to a certain extent, within which the balanced capacity requirements would be achieved. In

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such a way, the integrated production planning constitutes a closed loop system.

Production planning approaches based on master production scheduling, material requirement planning, capacity resource planning, *etc.*, have been well-established [5–7], providing the optimal configuration of resources and reducing production imbalance. However, in steel industry, its unique production process and product particularities complicate the problem when designing and implementing the production planning system. A review of planning and scheduling methods for the modern integrated process of steelmaking, continuous casting and hot rolling presents multiple models, algorithms and distributed agents [8]. Some efforts have been made to improve steel production and management. Zanoni and Zavanella [9] studied production–inventory system with finite capacity for steel manufacturing, where JIT environments were considered to find the optimal production scheduling and available warehouse space. Li and Shang [10] addressed the difficulties of linkage and synchronized problem and proposed an input–output model to coordinate large numbers of variables with minimum interfaces. Neureuther *et al.* [11] presented a three-tiered hierarchical production plan model, in which an aggregated linear programming model, a non-linear programming disaggregated model and a master production scheduling model were comprised in a make-to-order steel plant. Spengler *et al.* [12] developed a revenue management approach by formulating a multi-dimensional knapsack problem to provide decision support in order promising. Liu *et al.* [13] established an order-planning strategy to assign finish time of each process based on due date, capacity and other constraints. Zhang *et al.* [14] discussed a mixed integer nonlinear programming (MINLP) model that incorporates the inventory matching and production planning involving multiple objectives, such as penalty of earliness/tardiness, delivery time window, order cancelation, *etc.* Witt and Voss [15] described the planning model as a lot-sizing problem and implement the mid- to long-term production planning system based on standard software products from IBM and SAP.

It should be noted, however, that most of the above studies focused on the steel production planning under a single production scenario or deterministic customer service. As pointed out by Adam Ng and Johnson [16], customers can generally accept a set of different end-items complying with customization rules, rather than only one single specification. Iravani *et al.* [17] have defined the concept of a selective customer who is strict to his key items, but compromises his non-key items. The model for an assemble-to-order environment examines the customer satisfaction in different levels including item substitution. Balakrishnan and Geunes [2] have considered the product specification flexibility in a make-to-order specialty steel plate industry, in which customers are willing to accept steel plates within a certain range of sizes where the operation manager must decide the size of the end-item. As'ad and Demirli [18] have addressed downward substitution between two different grades of steel bars, which is applied to rolling horizon implementation of MPS in steel rolling mills. From the point of view of manufacturing process, Vanhoucke and Debels [19] have proposed a flexible capacity constraint called capacity shift, adding the unused capacity of previous day to the capacity of the current day, but the shift is limited by a threshold value to avoid unrealistic situations.

In this paper, a multi-period dynamic optimization approach is used to present the problem with multiple flexibility as an MINLP model. Different planning horizons and numbers of flexible scenarios are tested for complex manufacturing and operational environment, incorporating constraints of capacity, inventory, backlog, setup, raw material supply and flexible options concerning machine assignment, end-item matching and delivery. Binary variables are induced to represent the existence or nonexistence of rolling mill initialized setup, slab and plate matching, and slab supply. Bilinear terms are employed to express redistribution of unused capacity.

However, the proposed MINLP model may bring challenges to computational efforts and result in inconsistency in solution quality and time. Therefore, solution procedures with acceptable accuracy but faster response are required for timely and effective decision-making. Effective approaches have been proposed to solve MINLP model, such as branch-and-bound [20], outer approximation [21], Lagrangean decomposition [22], and evolution-based heuristic algorithm [23,24]; readers may refer to Grossmann [25] and Floudas and Gounaris [26] for a review. The main point in this paper is to eliminate the bilinear terms and transforms the original MINLP model into a mixed integer linear programming (MILP) model. Given either binary variable value or continuous variable value of a bilinear term, the bilinearity is reduced to be linear, so two different approaches are developed. The first one is based on linearization technique proposed by Glover [27]. The other one utilizes specific constraints on binary variables to reduce possible value combination and eliminates the bilinearity by enumerating the combination possibility. It provides a procedure to an exact solution of the original MINLP model, while the first approach transforms the MINLP model to an approximate MILP model. The results of the two approaches in terms of the solution quality and time are analyzed and compared in detail.

2. Statement of Problem

2.1. Manufacturing process

In a typical iron and steel enterprise, customer orders usually involve three primary products — plates, bars and wires, which are produced by different rolling mills in separated plants. Sintered iron ore is molten in the blast furnace and the molten iron is transported to primary steel-making shop. The primary steel-making process is mainly concerned with reduction in carbon content, addition of alloying elements and continuous casting into solid slabs, according to customer requirements on mechanical properties and physical dimensions. The steel slabs are cooled and stored in semi-product warehouse by their grade and dimensions. Each grade indicates a given quality expressed by several specific properties, such as toughness and ductility. The dimensions of the slabs are specified in terms of thickness, width, and length, which may change in a certain range. The slabs with the same grade and similar dimensions are grouped as steel ladle. The steel rolling shop mainly consists of two separated production lines with walking beam reheat furnaces and rolling mills. Selected slabs are first heated to high temperatures in the furnace with limited capacity, and then taken to corresponding rolling mills. *Via* several rolling procedures, such as roughing mill and finishing mill, the slabs are processed to thick and long plates, and then placed on cooling bed for some time, where the thickness of a plate is determined. After that, the plates are pushed out and clipped into smaller ones as desired width and length. At last, qualified plates are bound and stored in the end-item warehouse.

2.2. Flexible options

The manufacturing processes differ in their production efficiency, capacity and location. Operation specification only allows each kind of steel plates assigning one of the production lines during a period. A production line involves several process stages, where the capacity is determined by the bottleneck operation. The plates from a slab contain the same alloy with pre-specified thickness, and are cut with certain width and length. The feasible one-to-many relationship is called slab-to-plate matching rule. The total weight of the plates from a slab will be less than the weight of the slab, with some scraps produced when pruning.

Steel plate substitution is common in applications, so a certain quantity of one steel plate may be fulfilled with another. Since the thickness of steel plates is unchangeable, the substitution may be made either by higher grade plates or by appropriately pruned ones so as to be compatible with the requirements. We refer to these two flexibilities as grade substitution and conversion substitution. The steel plates substituted