Preprints of the 19th World Congress
The International Federation of Automatic Control
Cape Town, South Africa. August 24-29, 2014

A Production Planning Model for a Steel Plate Fabrication Plant with Flexible Customization and Manufacturing

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Abstract: With increased market competition and advances in modern manufacturing technologies, requirements on customer orders and manufacturing conditions have become more diversified. This paper addresses a dynamic production planning problem for a steel plate fabrication plant with practical flexibility of both customers and manufacturing, such as steel slab-plate matching rules, plate substitution options, production line assignment. These flexibility factors can provide the decision maker with auxiliary options to satisfy customer requirements through realizable production planning. The steel slab-plate matching rules combined with plate substitution options are visualized by a networked graph and formulated by a set based design. A mixed-integer nonlinear programming (MINLP) model that incorporates various manufacturing constraints and the flexibility is proposed to simultaneously optimize production strategy and provide practical managerial information such as backlogging/inventory level, capacity availability, and also steel slab demand. Linearization methods are used to transform the original MINLP problem into mixed integer linear programming (MILP) model resulting in easier and quicker solutions. A real industrial steel plate fabrication plant is used as a case and illustrates the effectiveness and applicability of the proposed method.

1. INTRODUCTION

Rapid changes in manufacturing industry and global market competition increase the requirement of developing effective and reliable operations management strategies. The aim of the operation management strategies is to assure that production is done in the best way possible. Finding the optimal production planning is not a trivial problem since the production operation environment is very flexible, and is subject to both varying customer requirements and varying manufacturing conditions. In this paper, the focus is on exploring how these flexibility factors and variations, encountered in many steel plate fabrication plants, can be translated into a production planning problem. The solution to the production planning problem can then be used to assure that the production is done in an optimized way.

The flexibility to be addressed can act at different levels or on different objects at different time scales. In the perspective of orders, customer requirements are not always fixed, as they may accept a list of steel plates (end-items) rather than a specific one. Therefore, the decision maker has some flexibility in choosing a preferred product to satisfy the customer orders, which can be optionally substituted by certain alternative en-items. This paper considers substitution among steel plates that can either take place by directly replacing a specific steel plate by that of higher grade (better quality) or by re-manufacturing steel plate with specific dimensions so that it can fulfil the requirements. In addition, variations in the steel fabrication environments complicate the operations and bring more flexible conditions, such as flexibility in steel slab matching, production routing assignment, capacity allocation and even supplies of steel slabs. Under these varying conditions, a systematic approach is required when designing an effective production planning strategy that should operate both reliably and economically.

In the past decades, several researchers have drawn attention to improving the steel production and management. Zanoni and Zavanella (2005) studied the production-inventory system with finite capacity for steel fabrication, where just-in-time (JIT) environments are considered to find the optimal production scheduling and available warehouse space. Neureuther et al. (2004) presented a three-tiered hierarchical production plan (HPP) model in which an aggregated linear programming (LP) model, a non-linear programming (NLP) disaggregated model and a master production schedule (MPS) model were comprised in a make-to-order (MTO) steel plant. Spengler et al. (2007) developed a revenue management approach through formulating a multi-dimensional knapsack problem to provide decision support in order promising. Liu et al. (2006) established an order-planning strategy to assign finish time of each process based on due date, capacity and other constraints.

However, the above researches address the production planning problem only under fixed production and service scenarios. Very little research has focused on the existing flexibility that is presented in production planning for iron and steel enterprises. Balakrishnan and Geunes (2003) considered the product-specification flexibility in a MTO specialty steel plate industry. In this article, customers are willing to accept steel plates within a certain range of sizes where the operations manager must decide the size of the finished item. As'ad and Demirli (2010) addressed downward substitution between the two different grades of steel bars which is applied to rolling horizon implementation of MPS in steel rolling mills. The above two approaches address the flexibility of sizes and grades of the steel end-item respectively.

In this paper, based on the studies of production planning strategies and production characteristics in steel fabrication plant, a production planning model for steel plates is presented. The production planning model will optimize production-inventory system, which incorporates the flexible operations including steel slab-plate matching, steel plate substitution, production routing assignment and capacity allocation. A networked graph and a set based approach are proposed to depict and formulate the steel slab-plate matching rules and plate substitution options. The design and optimization of the proposed model lead to a complex MINLP problem which might result in massive computational efforts. Therefore, linearization techniques are developed to transform the original MINLP model into an MILP model. Finally, the proposed approach is applied to a case study, in order to illustrate its effectiveness and potential.

2. FLEXIBILITY FOR STEEL PLATE FABRICATION

In steel plate fabrication plant, products of the primary steel-making process called as steel slabs are cooled and stored in semi-product warehouse for steel plates and defined by their steel grade and dimensions. The selected slabs are firstly heated up to high temperatures in the furnace with a limited capacity, then taken to the corresponding rolling production lines. Via several rolling procedures, such as roughing mill and finishing mill, the slabs are processed into thick and long plates, and then placed on cooling bed for some time, where the thickness of a plate is determined. The dimensions of the slabs are specified in terms of thickness, width, and length, which changes in a certain range depending on slab design. Therefore, slabs with the same grade and similar dimensions are grouped as steel ladle.

In practice, the external or internal requirements of the customers may be somewhat vague, so that decision maker has flexibility in choosing the steel plates to satisfy the orders. In another word, a certain quantity of one steel plate can be fulfilled using another one. Due to the thickness of steel plates is unchangeable, substitution may either occur by replacing plates of lower grade by that of higher grade or by appropriate pruning so as to be compatible with the requirements. We refer to these two kinds of flexibility as grade substitution and conversion substitution respectively. When the dimensions are the same, grade substitution can fulfil the steel plate shortage of lower grade directly with a substitution ratio of 1:1, which means one quantity unit of plate can substitute exactly one quantity unit of the specific plate. The conversion substitution ratio in this case should be more than 1, where cutting or pruning will result in an extra scraps. Fig. 1 explains the grade and conversion substitution. Here, we present four kinds of steel plates with the same thickness, of which P1, P2 are the same size while P3, P4 are smaller in width and length. Case 1 and 2 represent grade substitution and conversion substitution respectively. For case 3, P1 is first used to replace P4 acted as low grade, then cut or pruned to the required dimension of P4. To formulate the substitution options, a set S is used to represent the feasible substitution, where $(i,i') \in S$ means plate i' can be substituted by plate i. $P_i = \{i' \mid (i,i') \in S\}$ is set of plates which can be substituted by plates i. $Q_i = \{i' \mid (i',i) \in S\}$ is set of plates which can substitute plates i.

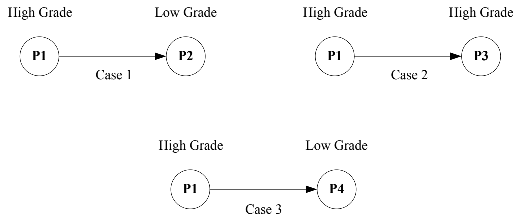

Fig. 1. Steel plate substitution options

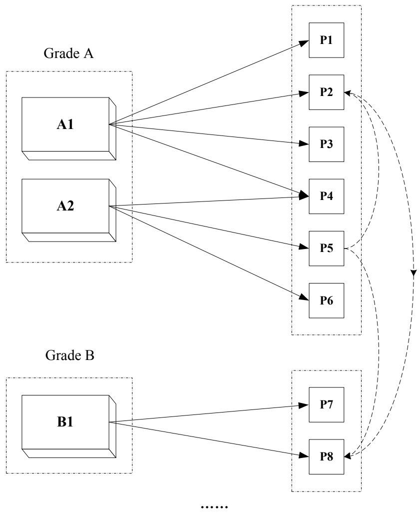

Fig. 2. Matching cases from steel slabs to plates considering plate substitution

Moreover, since steel slabs and plates are both categorized as different alloys and dimensions, all plates matched to a slab must contain the same alloy; each kind of slab can be rolled into several plates with pre-specified thickness, and also cut within certain width and length. The feasible one-to-many relationship is called slab-to-plate matching rule. When the substitution options combine with the slab-to-plate matching rule, the relationship between steel slabs and plates is constructed as a network. The complexity increases as a certain steel plate may substitute or be substitute in according to the above three cases, and under restrictions of the matching rule. Fig. 2 illustrates how substitution options work when considering slab-to-plate matching rule, in which cuboids and circles represent the steel slabs and plates respectively. We assume that grade A is higher than grade B, and A1, A2 differ in their dimensions. Solid arrows give the matching relationship between steel slabs and plates, while dotted arrows indicate the three kinds of substitution as shown in Fig. 2, where P2-to-P8 maps case 1, P5-to-P2 maps case 2, P5-to-P8 maps case 3. Then P2 is able to substitute P8, and is permitted to be substituted by P5 in the meantime. Demand for P8 can be satisfied through three approaches now: B1-to-P8, A1-via-P2-to-P8, and A2-via-P5-to-P8. Similarly, a set R is used to present the feasible matching rules. $B_j = \{i \mid (i,j) \in R\}$ presents set of plates which can be matched by slabs *j*. Therefore, we find that multipath strategy from steel slabs to plates provides more flexible routings.

The steel plate fabrication plant mainly consists of several separated rolling production lines with walking beam reheat furnaces and rolling mills. The rolling production lines mentioned above differ in their production efficiency, capacity and location. Operation specification only allows each kind of steel plate assigning one of the production lines during a period. The production lines involve several process stages, where the rhythm or capacity is determined by bottleneck operation. In order to avoid a structural under-use of the available capacity, Vanhoucke and Debels (2009) introduced an unused capacity of the previous period to the capacity of current period. We refer to this capacity flexibility as capacity shift. The capacity for the next period is allocated based on both the capacity usage amount for the current period and the quantity of steel plates required to be produced for the next period. Therefore, the capacity allocation for each production line is also flexible.

3. MATHEMATICAL MODELING APPROACH

Considering the actual operation situations in an iron and steel enterprise in China, in this paper, both the objective function and various constraints are set up that incorporates the flexible conditions. More precisely, the objective of the optimal production planning problem is to achieve the minimum operating cost as a sum of seven different cost functions: machine assignment cost, setup cost, production cost, inventory holding cost, substitution cost, capacity utilization penalty cost and backlogging penalty cost. Besides, the problem is subject to several different constraints involving machine assignment, capacity, setup, slab-plate matching, inventory and other auxiliary constraints.

3.1 Objective Function

The objective function for the proposed optimization problem is chosen to be minimizing operating costs as follows:

$$C = C_{assign} + C_{setup} + C_{prod} + C_{inv} + C_{blance} + C_{back} + C_{subs} \quad (1)$$

$$C_{assign} = \sum_{m \in M} \sum_{j \in J} ca_{jm} \sum_{d} y_{jmd} \quad (2)$$

$$C_{setup} = \sum_{d} \sum_{m \in M} cmi_{md} z_{md} \quad (3)$$

$$C_{prod} = \sum_{d} \sum_{m \in M} \sum_{j \in J} \sum_{i \in I} cp_{ijmd} mx_{ijmd} \quad (4)$$

$$C_{inv} = \sum_{d} \left(\sum_{j \in J} cib_{jd} Ib_{jd} + \sum_{i \in I} cif_{id} Ip_{id} \right) \quad (5)$$

$$C_{balance} = \sum_{d} \sum_{m \in M} \alpha_{md} \left(ta_{md} + \Delta ta_{md-1} z_{md} - tu_{md} \right) \quad (6)$$

$$C_{back} = \sum_{d} \sum_{i \in I} cba_{id} mba_{id} \quad (7)$$

$$C_{subs.} = \sum_{d} \sum_{i \in I} \sum_{i' \in P_i} cr_{ii'd} \theta_{ii'} ms_{ii'd} \quad (8)$$

where y_{jmd} is binary variable to couple each slab *j* to rolling mill *m*; ca_{jm} is the cost of unit quantity of slabs to be assigned to each production line; z_{md} is binary variable that indicates if initialized setup occurred at the beginning of each period; cmi_{md} is the cost of initialized setup; mx_{ijmd} is the quantity of plate *i* to be produced from slab *j*; cp_{ijmd} is unit production cost; Ib_{jd} and Ip_{id} are steel slab and plate inventory level; cib_{jd} and cif_{id} are unit holding cost of the two inventory respectively; α_{md} is penalty cost of unit surplus capacity; ta_{md} is capacity to be allocated; Δta_{md-1} unused capacity of previous period; tu_{md} is capacity to be occupied; mba_{id} is quantity of backlogging plates to be produced; cba_{id} is cost of unit backlogging quantity; $ms_{ii'd}$ is substitution quantity of plate *i* used to fulfil demand of plate *i'*; $\theta_{ii'}$ is substitution ratio; $cr_{ii'd}$ is unit substitution cost.

Eq.(2) refers to the assignment cost of steel slab coupled to production line. Eq.(3) and (4) refer to the setup and production cost. Eq.(5) refers to the inventory holding cost associated with raw material and end-item inventory. Eq.(6) and (7) present the penalty cost of surplus capacity in proportion to the quantity of unused capacity, and backlogging cases respectively. Eq. (8) presents the substitution cost involves those of steel grades substitution and conversion substitution

3.2 Assignment Constraints

In order to process all operations all at once, each plate order must select a unique production line. Under the backlogging case, the order may not be assigned to any of production lines. Therefore, the assignment constraints are presented by:

$$\sum_{m \in M} x_{imd} \le 1 \quad \forall i, d \quad (9)$$

where x_{imd} is binary variable to couple each plate to each production line.

3.3 Capacity Constraints

Each production line has a limited capacity expressed in hours, which may not be exceeded by all assigned steel plate orders as eq.(10). In order to avoid a structural under-use of the available capacity, unused capacity of the previous period Δta_{md-1} is added (Vanhoucke and Debels 2009). The capacity to be allocated should be limited by upper and lower bound as eq.(11). Setup occurred at the beginning of each period as initialization or inspection as eq. (12)

$$ta_{md} + \Delta ta_{md-1} z_{md} \geq tu_{md} \quad \forall m,d \tag{10}$$

$$\underline{ta_{md}} \leq ta_{md} \leq \overline{ta_{md}} \ \forall m,d \tag{11}$$

$$ts_{md} = z_{md} tmi_{md} \quad \forall m,d \tag{12}$$

where $\overline{ta_{md}}$ and $\underline{ta_{md}}$ are upper and lower bound of the available capacity; tmi_{md} is initialization time if setup occurred; ts_{md} is setup time.

The available capacity would be pre-allocated based on quantity of steel plates to be produced for the next and the utilization situation for the current period. Capacity pre-allocation constraints are shown in eq.(13). Capacity utilization situation is presented in eq.(14), which involves capacity occupied by both production and setup. Relationship of production quantity and the occupied capacity is presented is eq.(15). The unused capacity equals to difference between allocated available capacity and utilized capacity as eq.(16). Continuous variables related to production quantity and capacity should not be negative as eq.(17).

$$\sum_{m \in M} \left(ta_{md} + \Delta ta_{md-1} z_{md} \right) = \omega_d \sum_{m \in M} tu_{md-1} \quad \forall d \tag{13}$$

$$tu_{md} = tp_{md} + ts_{md} \ \forall m,d \tag{14}$$

$$tp_{md} = \sum_{j \in J} \frac{my_{jmd}}{\eta_{jmd}} \quad \forall m,d \tag{15}$$

$$\Delta ta_{md} = tu_{md} - ts_{md} \quad \forall m,d \tag{16}$$

$$mx_{ijmd}, my_{jmd}, ta_{md}, tu_{md}, tp_{md}, ts_{md}, \Delta ta_{md} \geq 0 \quad \forall i,j,m,d \tag{17}$$

3.4 Slab-plate Matching Constraints

To address corresponding relation between steel slabs and plates, yield ratio is introduced. All plates based on slab-plate matching rules can be mapped to specific steel slabs. The slab-plate matching constraints are shown as following:

$$my_{jmd} = \sum_{i \in B_j} \frac{mx_{ijmd}}{\gamma_{ijmd}} \quad \forall j,m,d \tag{18}$$

$$my_{jmd} = mb_{jd} nb_{jmd} \quad \forall j,m,d \tag{19}$$

where γ_{ijmd} is yield rate of steel plate *i* produced from slab *j;* mb_{jd} is weight of one piece of slab. nb_{jmd} is the number of slabs to be assigned.

3.5 Inventory Constraints

In practice, steel slabs and plates are stored in different warehouse, so the two inventory balance equations are formulated separately. Backlogging cases and plate substitution are incorporated in the equations. These two inventory constraints are presented by eq.(20) and (21).

$$Ib_{jd} = Ib_{jd-1} + mp_{jd} - \sum_{m \in M} my_{jmd} \quad \forall j,d \tag{20}$$

$$\begin{aligned} Ip_{id} - mba_{id} = Ip_{id-1} - mba_{id-1} + \sum_{m \in M} \sum_{j \in J} mx_{ijmd} \\ - md_{id} + \sum_{i' \in Q_i} \frac{ms_{i'id}}{\theta_{ii'}} - \sum_{i' \in P_i} \frac{ms_{ii'd}}{\theta_{i'i}} \quad \forall i,d \end{aligned} \tag{21}$$

where mp_{jd} is quantity of slabs supplied at the beginning of period *d*; md_{id} is steel plates demand at the end of period *d*.

Safety inventory level is often set relative to the distribution of demand over some common situations. The two inventory levels must limited by the safety levels as presented by eq.(22) and (23). Substitution quantity and backlogging level must not be negative as shown in (24)~(26).

$$Ib_{jd} \geq Ibs_{jd} \quad \forall j,d \tag{22}$$

$$Ip_{id} \geq Ips_{id} \quad \forall i,d \tag{23}$$

$$ms_{ii'd} \geq 0 \quad \forall i \in I, \forall i' \in P_i \tag{24}$$

$$ms_{i'id} \geq 0 \quad \forall i \in I, \forall i' \in Q_i \tag{25}$$

$$mba_{id} \geq 0 \quad \forall i,d \tag{26}$$

where Ibs_{jd} and Ips_{id} are steel slab and plate safety inventory level respectively.

3.6 Logic Constraints

With general binary variables x_{imd} , y_{jmd} and z_{md} , the relationships between these binary variables and continuous decision variables are:

$$x_{imd} = 1 \Leftrightarrow \sum_{j \in J} mx_{ijmd} > 0 \quad \forall i,m,d \tag{27}$$

$$x_{imd} = 0 \Leftrightarrow \sum_{j \in J} mx_{ijmd} = 0 \quad \forall i,m,d \tag{28}$$

$$y_{jmd} = 1 \Leftrightarrow \sum_{i \in I} mx_{ijmd} > 0 \quad \forall j,m,d \tag{29}$$

$$y_{jmd} = 0 \Leftrightarrow \sum_{i \in I} mx_{ijmd} = 0 \quad \forall j,m,d \tag{30}$$

$$z_{md} = 1 \Leftrightarrow ta_{md} > 0 \ \ \forall m,d \tag{31}$$

$$z_{md} = 0 \Leftrightarrow ta_{md} = 0 \ \ \forall m,d \tag{32}$$

$$x_{imd}, y_{jmd}, z_{md} \in \{0,1\} \ \ \forall i,j,m,d \tag{33}$$

3.7 Initialization Constraints

Without loss of generality, the initial two inventories are set to the corresponding safety inventory level by eq.(34) and (35). The initial value of surplus capacity and backlogging level are set to be zero by eq.(36) and (37)

$$Ib_{j0} = Ibs_{j0} \ \ \forall j \tag{34}$$

$$If_{i0} = Ifs_{i0} \ \ \forall i \tag{35}$$

$$\Delta ta_{m0} = 0 \ \ \forall m \tag{36}$$

$$mba_{i0} = 0 \ \ \forall i \tag{37}$$

4. MODEL SIMPLIFICATION AND SOLUTION

The equations or inequations described in the above optimization model contain nonlinear terms in eq. (6), (10), (13) and (27) ~ (32). The presence of integer variables along with nonlinear terms makes the designed model a MINLP problem. However, solving such MINLP problem will require large computational efforts and may result in inconsistency in solution quality. So it is necessary to check and simplify the characteristic of the model before starting optimization procedure.

Binary variables in the above optimization model are employed to express the utilization of steel slabs and assignment, or production status of steel plates. Considering the relationship between binary and continuous variables, eq. (27) ~ (32) can be replaced by linear inequations as follows.

$$x_{imd} Lmx_{imd} \le \sum_{j \in J} mx_{ijmd} \le x_{imd} Umx_{imd} \ \ \forall i,m,d \tag{38}$$

$$y_{jmd} Lmy_{jmd} \le \sum_{i \in I} mx_{ijmd} \le y_{jmd} Umy_{jmd} \ \ \forall j,m,d \tag{39}$$

$$z_{md} Lta_{md} \le ta_{md} \le z_{md} Uta_{md} \ \ \forall m,d \tag{40}$$

where Umx_{imd}, Umy_{jmd} and Uta_{md} represent the respective upper bounds on variables and terms $\sum_{j \in J} mx_{ijmd}$, $\sum_{i \in I} mx_{ijmd}$ and ta_{md}, while Lmx_{imd}, Lmy_{jmd} and Lta_{md} indicate the corresponding lower bounds.

The nonlinear terms in eq.(6), (10) and (13) are bilinearity to describe the usage of surplus capacity where binary variable z_{md} is multiplied by continuous variables Δta_{md-1}. Some linearization approaches were proposed in literatures to address the bilinear terms (Glover 1975, Sherali and Alameddine 1992). In this paper, based on the linearization formulation technique for mixed 0-1 nonlinearity by Glover (1975), the bilinear terms in the model are replaced by new continuous variables and relaxed by lower and upper bound. Therefore, the bilinear terms in eq.(6), (10) and (13) can be replaced by continuous variable V_{md} and reformulated as follows:

$$L\Delta ta_{md} z_{md} \le V_{md} \le U\Delta ta_{md} z_{md} \ \ \forall m,d \tag{41}$$

$$\begin{aligned} \Delta ta_{md-1} - U\Delta ta_{md}(1 - z_{md}) \le V_{md} \le \Delta ta_{md-1} \\ - L\Delta ta_{md}(1 - z_{md}) \ \ \forall m,d \end{aligned} \tag{42}$$

where $U\Delta ta_{md}$ and $L\Delta ta_{md}$ represent the upper and lower bounds of the term Δta_{md-1}.

Based on the above simplification strategy, the original MINLP optimization problem is now transferred to the following MILP problem (Floudas 1995). LINGO system provides the access to MILP solvers (Schrage 2006).

5. CASE STUDY

A case study is presented to demonstrate the applicability and effectiveness of the proposed method. The data for the case study were obtained from a large iron and steel enterprise in south China, where two production lines are set in its steel plate fabrication plant. The planning horizon is tested in days. Fig. 3 presents the steel slab-plate matching rules and plate substitution options under consideration, where solid lines represent the steel slab-to-plate matching rules, the dash lines represent the plate-to-plate substitution options with substitution ratio of 1, and dash-dotted lines represent the plate-to-plate substitution options with substitution ratio larger than 1. A1, A2 and B1 are three specifications of steel slabs. A1 are thicker than A2, but both are of the same alloy. B1 differs with A1 and A2 both in dimension and alloy. P1~P8 are eight specifications of steel plates, where grade substitution and conversion substitution may occur independently or simultaneously. Table 1 gives steel plate demand during each period based on customer orders.

Table 1. Steel plate demand data for each period

Steel plate specification	Demand/t			
	d=1	d=2	d=3	d=4
j=1	135	130	160	140
j=2	120	0	0	0
j=3	130	130	160	165
j=4	110	125	155	140
j=5	125	120	0	0
j=6	0	135	170	165
j=7	130	140	150	170
j=8	125	140	170	140

The optimal production quantity of steel plates for each period is presented in Table 2. It can be seen that the optimal strategy can satisfy the order requirements in most cases. For the first period, the production quantity of each steel plate is equal or larger than the demand, so that the surplus inventory can be used to fulfil the demand when production quantity is not enough.

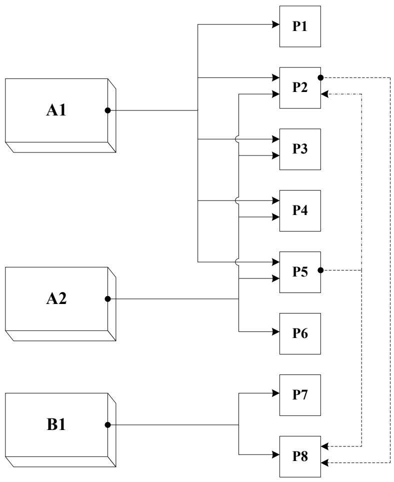

Fig. 3. Steel slab-to-plate and plate-to-plate network for the case study

Table 2. Optimal Production Strategy for each period

Steel plate specification	Production quantity/t			
	d=1	d=2	d=3	d=4
j=1	144	148	132	130
j=2	120	0	50	0
j=3	130	130	160	165
j=4	110	125	155	140
j=5	125	120	0	0
j=6	73	70	162	165
j=7	136	134	150	110
j=8	145	148	90	140

Table 3. Cost comparison between flexible and deterministic scenarios

Cost ($)	Model A	Model B
Inventory	6102	5853
Backlogging penalty	17214	9120
Production	423580	426639
Total	474225	470068

To present the effectiveness of the flexibility considered in this paper, computational results of the model under single deterministic scenario (Model A) are compared with that of the proposed model (Model B), as shown in Table 3. The proposed approach considering the flexibility has a total operation cost of $\$470.068\times10^3$ over the planning horizon and results in a saving of 0.88% compared to an existing operation strategy under deterministic scenario.

6. CONCLUSION

In this work, flexibility issues are taken into account for the optimal design of production planning in steel plate fabrication plant to obtain realistic solutions. Most previous approaches neglect these concerns. Steel slab-plate matching rules, plate substitution options and unused capacity re-allocation are incorporated in the planning scheme. A networked graph and set based approach are used to formulate the matching rules and substitution. The corresponding production planning problem is mathematically formulated into a MINLP problem. To obtain the solutions with less computational efforts but acceptable accuracy, linearization methods are used to simplify the model and transform the original MINLP formulation to a MILP model. Using a case study based on industrial application, it is shown that the proposed approaches can operate with a higher flexibility and lower total costs, compared with the existing method. The proposed optimal production planning strategy can provide important operation and management information for decision makers in iron and steel enterprises.

REFERENCES

As'ad, R. and Demirli, K. (2010). Production scheduling in steel rolling mills with demand substitution: Rolling horizon implementation and approximations. *International Journal of Production Economics,* **126**(2), 361-369.

Balakrishnan, A. and Geunes, J. (2003). Production planning with flexible product specifications: an application to specialty steel manufacturing. *Operations Research,* **51**(1), 94-112.

Floudas, C. A. (1995). *Nonlinear and mixed-integer optimization: fundamentals and applications,* Oxford University Press, Place.

Glover, F. (1975). Improved linear integer programming formulations of nonlinear integer problems. *Management Science,* **22**(4), 455-460.

Liu, S., Tang, J. and Song, J. (2006). Order-planning model and algorithm for manufacturing steel sheets. *International Journal of Production Economics,* **100**(1), 30-43.

Neureuther, B. D., Polak, G. G. and Sanders, N. R. (2004). A hierarchical production plan for a make-to-order steel fabrication plant. *Production Planning & Control,* **15**(3), 324-335.

Schrage, L. (2006). *Optimization Modeling with LINGO. 2006,* Place.

Sherali, H. D. and Alameddine, A. (1992). A new reformulation-linearization technique for bilinear programming problems. *Journal of Global Optimization,* **2**(4), 379-410.

Spengler, T., Rehkopf, S. and Volling, T. (2007). Revenue management in make-to-order manufacturing—an application to the iron and steel industry. *OR spectrum,* **29**(1), 157-171.

Vanhoucke, M. and Debels, D. (2009). A finite-capacity production scheduling procedure for a Belgian steel company. *International Journal of production research,* **47**(3), 561-584.

Zanoni, S. and Zavanella, L. (2005). Model and analysis of integrated production–inventory system: The case of steel production. *International Journal of Production Economics,* **93**, 197-205.