Modeling and Multi-objective Optimization Method for Steel Production Planning and Its Application

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***Abstract*—The motivation for this study is a problem instance in the steel production process. The production orders demand a large number of products to be produced in the flexible factory where contains many production units. Each product can be produced from corresponding raw materials on different routings during the time period. A novel approach is presented in this paper for modeling the production process and optimizing the production planning. An improved multi-objective optimization is proposed, which subjects to minimizing production cost and minimizing inventory cost. The proposed method for optimization considers manufacturing capacity constraints, raw materials and finished products constraints, inventory constraints and tardiness constraints, etc. This method takes into account multiple routings, multiple inputs and outputs and multiple time periods and a deterministic optimization methodology is applied to solve the production planning problem. Finally, a real case study is presented to validate the applicability of the presented approach.**

I. INTRODUCTION

Many manufacturing enterprises are forced to optimize the production process to win the business in the globalised market. The steel industry is an important basic industry for the development of industrial economy. Nowadays, the steel industries are facing challenges of stricter regulation and increasing varying requirements of customers. To ensure optimum benefit, the management and optimization of steel production planning is becoming increasingly important.

Many investigations have been reported in the literatures on steel production planning. M. Vanhoucke et al. [1] presented a finite-capacity production scheduling algorithm at a middle-term planning horizon level for the integrated steel company. L.X. Tang et al. [2] gave a comparative analysis on different production processes in steel company and reviewed the planning and scheduling systems. S. Zanoni et al. [3] addressed the production inventory system with finite capacity in steel manufacturing and considered to find the optimal production scheduling and available warehouse space in just-in-time environments. S.X. Liu et al. [4] established an order-planning model to minimize tardiness cost, balance utility of capacities and minimize inventory cost based on due date, capacity and other constraints. M.P. Biswal et al. [5] developed a multi-choice linear programming model in order to integrate the planning sub-functions into a single planning operation for steel plant. T. Sawik [6] considered long-term production scheduling in the make-to-order manufacturing and proposed a lexicographic approach with a hierarchy of integer programming formulations.

However, most studies focus on single production routing and single time period in steel production process, few accounts for multi-routing, multi-input and output and multi-period optimization strategy. S. Sheikh [7] presented a multi-objective flexible flow shop scheduling problem with limited time lag between stages. J. Miltenburg [8] proposed a heuristic solution for the single time-period production planning problem where products have alternative routings. In the practical steel production process, a large number of different productions are produced in the flexible factory which contains many production units. The used sequence of production units forms the production routing to produce the products from raw materials. According to the requirements of finished product orders, some specific raw materials can be used to produce the corresponding products on the selected routings. In order to obtain the maximum profit, the objective is to minimize the production and inventory cost given the constraints in the production planning time period at the steel company. This is described as the multi-routing, multi-input and output, multi-period production planning problem.

In this study, a novel approach is presented for modeling and optimization of steel production process where different products are produced from different raw materials on multiple routings during multiple time periods. The objective functions of the multi-objective optimization are minimizing production cost and minimizing inventory cost. The proposed methodology for the multi-objective optimization of steel production process considers manufacturing capacity constraints, raw materials and finished products constraints, inventory constraints and tardiness constraints, etc. To make the approach more suitable for the real practical production process, the alternative routings and multiple time periods are taken into account. The optimization model is converted into a MINLP problem and the suitable optimization strategy is determined by an optimization solution. To demonstrate the effectiveness of the presented model, a real case study in steel production process is introduced. This paper is organized as follows. An introduction to this paper is provided and the production planning problem is proposed in section 1; In section 2, the optimization constraints of steel production process are given; formulation and solution strategy of the multi-objective optimization problem is analyzed in section 3. A real case study is given and validates the optimization strategy in section 4. Finally, the conclusions are drawn in section 5.

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II. OPTIMIZATION CONSTRAINTS

To select the appropriate routing and optimize the manufacturing routing, many practical constraints should be considered, such as manufacturing capacity, raw materials and finished products constraints, routing selecting constraints, inventory and tardiness constraints. All possible connections from raw materials to finished products should be taken into account. And binary variables are employed to decide whether the available routing is chosen or not. In all, manufacturing routing is optimized to effectively utilize the existing facilities and meet the anticipated demand at the most extent for the minimum total cost and maximum product yield profit.

A. Manufacturing capacity constraints

To keep the manufacturing process stable and safety, the constraints imposed by manufacturing facilities cannot be violated and the manufacturing quantity should meet the facilities capacity requirement.

$$\sum_{j=1}^{J}\sum_{i=1}^{I}\sum_{k=1}^{K}\left[\alpha_{m,j,t}\cdot\left(QF_{k,i,j,t}+QT_{k,i,j,t-1}\right)\right]\le CF_{m,t},\forall m\in FSR_j,\forall t\in T \quad (1)$$

where $QF_{k,i,j,t}$ and $QT_{k,i,j,t-1}$ are the finished product quantity and the tardiness quantity respectively. $\alpha_{m,j,t}$ is used to select the used facility and $CF_{m,t}$ is the facility anticipated capacity.

B. Raw materials and finished products constraints

Due to the processing reason, there are different yield rates from raw materials to finished products on different available routings. The relation between raw materials and finished products can be described as

$$\sum_{i=1}^{I}\left[\theta_{k,i,j,t}\cdot\left(\frac{QF_{k,i,j,t}}{\gamma_{k,i,j,t}}+\frac{QT_{k,i,j,t-1}}{\gamma_{k,i,j,t-1}}\right)\right]=QM_{k,j,t},\forall k\in RMR_j,\forall j\in J,\forall t\in T \quad (2)$$

where $QM_{k,j,t}$ is the used raw material quantity, $\theta_{k,i,j,t}$ is used to decide the routing and $\gamma_{k,i,j,t}$ is the yield rate.

C. Routing selecting constraints

In every time period, each finished product is produced on one routing using one raw material.

$$\sum_{j=1}^{J}\theta_{k,i,j,t}\le 1,\forall k\in RMR_j,\forall i\in FPR_j\forall t\in T \quad (3)$$

With general binary variables $\theta_{k,i,j,t}$, the relationships between $\theta_{k,i,j,t}$ and $QF_{k,i,j,t}$ are

$$\theta_{k,i,j,t}=1\Leftrightarrow QF_{k,i,j,t}>0,\forall k\in RMR_j,\forall i\in FPR_j,\forall j\in J,\forall t\in T \quad (4)$$

$$\theta_{k,i,j,t}=0\Leftrightarrow QF_{k,i,j,t}=0,\forall k\in RMR_j,\forall i\in FPR_j,\forall j\in J,\forall t\in T \quad (5)$$

D. Inventory and tardiness constraints

There are raw materials inventory and finished products inventory in the manufacturing process. The raw materials purchased or produced from primary operations are held in the raw materials inventory, while the finished products produced by finishing operations are stocked to delivery in the finished products inventory. Because the supply and consumption of raw materials change in the manufacturing process, raw materials inventory keep dynamic equilibrium. The balance for raw materials inventory is

$$IM_{k,t}=IM_{k,t-1}+SM_{k,t}-\sum_{j=1}^{J}QM_{k,j,t},\forall k\in K,\forall t\in T \quad (6)$$

where $IM_{k,t}$ and $SM_{k,t}$ are inventory level and supply capacity of raw material respectively.

Due to production, delivery and tardiness of finished products, finished products inventory stay dynamic change. The finished products inventory balance is

$$IP_{i,t}=IP_{i,t-1}+\sum_{k=1}^{K}\sum_{j=1}^{J}\left(QF_{k,i,j,t}+QT_{k,i,j,t-1}\right)-\left(DF_{i,t}-\sum_{k=1}^{K}\sum_{j=1}^{J}QT_{k,i,j,t}\right),\forall i\in I,\forall t\in T \quad (7)$$

where $IP_{i,t}$ and $DF_{i,t}$ are the inventory level and anticipated demand of finished product separately.

The inventory is required to ensure the safety level, and the amount of raw materials and finished product held in the inventory never exceed its maximum inventory capacity respectively. The limits are

$$IR_{\min,t}\le\sum_{k=1}^{K}IM_{k,t}\le IR_{\max,t},\forall t\in T \quad (8)$$

$$IF_{\min,t}\le\sum_{i=1}^{I}IP_{i,t}\le IF_{\max,t},\forall t\in T \quad (9)$$

where $IR_{\min,t}$ and $IR_{\max,t}$ are the limitation of raw materials while $IF_{\min,t}$ and $IF_{\max,t}$ are the limitation of finished products.

E. Variable range constants

The continue variables in the model should be nonnegative.

$$QM_{k,j,t},QF_{k,i,j,t},QT_{k,i,j,t},CF_{m,t},IM_{k,t},IP_{i,t},SM_{k,t},DF_{i,t}\ge 0,$$

$$\forall k\in K,\forall i\in I,\forall j\in J,\forall t\in E,\forall t\in T \quad (10)$$

$$\alpha_{m,j,t}\in\{0,1\},\forall m\in FSR_j,\forall j\in J,\forall t\in T \quad (11)$$

$$\theta_{k,i,j,t}\in\{0,1\},\forall k\in K,\forall i\in I,\forall j\in J,\forall t\in T \quad (12)$$

F. Initialization

Considering the iteration relationships of inventory quantity and tardiness quantity, their initial values should be given. Without loss of generality, the initial raw materials inventory quantity and finished products inventory quantity are equal to the safety inventory level respectively, which also ensure that the demand for each finished products throughout the planning horizon is met. Because there is no tardiness of finished products, the initial values of tardiness are set to zero.

$$IM_{k,0}=IR_{\min,0},\forall k\in K \quad (13)$$

$$IP_{i,0}=IF_{\min,0},\forall i\in I \quad (14)$$

$$QT_{k,i,j,0}=0,\forall k\in RMR_j,\forall i\in FPR_j,\forall j\in J \quad (15)$$

III. FORMULATION OF THE PRODUCTION OPTIMIZATION PROBLEM AND SOLUTION STRATEGY

Choosing different routings for manufacturing has a direct effect on production cost and inventory level, so minimizing production cost and minimizing inventory cost are the objective functions of the multi-routing, multi-input and output, multi-period production optimization problem in this paper. The first objective function for the optimization problem is the production cost,

$$F_1 = f_{ppc} + f_{mpc} + f_{ptc} \tag{16}$$

where f_{ppc}, f_{mpc} and f_{ptc} are the total cost of raw materials utilized, manufacturing process and tardiness respectively in the planning horizon.

The total purchasing and production cost of raw materials utilized in the manufacturing process is represented as

$$f_{ppc} = \sum_{t=1}^{T}\sum_{j=1}^{J}\sum_{k=1}^{K}\left(PR_{k,t}\cdot QM_{k,j,t}\right) \tag{17}$$

where $PR_{k,t}$ is the purchasing and production cost of raw material per unit.

The total manufacturing process cost of finished products could be calculated by

$$f_{mpc} = \sum_{t=1}^{T}\sum_{j=1}^{J}\sum_{i=1}^{I}\sum_{k=1}^{K}\left[PC_{k,i,j,t}\cdot\left(QF_{k,i,j,t}+QT_{k,i,j,t-1}\right)\right] \tag{18}$$

where $PC_{k,i,j,t}$ is production cost of finished product per unit.

The total tardiness penalty cost of finished products is expressed as

$$f_{ptc} = \sum_{t=1}^{T}\sum_{j=1}^{J}\sum_{i=1}^{I}\sum_{k=1}^{K}\left(PT_{i,t}\cdot QT_{k,i,j,t-1}\right) \tag{19}$$

where $PT_{i,t}$ is tardiness penalty of finished product per unit.

The second objective function is the inventory cost,

$$F_2 = f_{rmic} + f_{fpic} \tag{20}$$

where f_{rmic} is the total inventory holding cost of raw materials and f_{fpic} is the total finished products holding cost.

The total inventory holding cost of raw materials is described as

$$f_{rmic} = \sum_{t=1}^{T}\sum_{k=1}^{K}\left(PM_k\cdot IM_{k,t}\right) \tag{21}$$

where PM_k is the inventory cost of holding one unit of raw material.

The total finished products inventory holding cost can be calculated by

$$f_{fpic} = \sum_{t=1}^{T}\sum_{i=1}^{I}\left(PF_i\cdot IP_{i,t}\right) \tag{22}$$

where PF_i is the inventory cost of holding one unit of finished product.

It is appropriate to solve the multi-routing, multi-input and output, multi-period production optimization problem by using multi-objective optimization strategy, which aims at searching for one or more satisfying solutions in Pareto optimal set. Multi-objective optimization strategy contains two main algorithms: one is converting the multi-objective optimization problems to a single objective optimization problem using some methods, and another is selecting the satisfying solutions using some trade-off criterion in the Pareto optimal set. To get the Pareto optimal set, mathematical programming approach and genetic algorithm are applicable. Most multi-objective evolutionary algorithms use non-dominated sorting to promote population evolution; however, non-dominated sorting doesn't play an efficient role at later evolution process, resulting in low convergence rate, local minimal and poor global search ability. In this study, the model contains numerous binary and continuous variables, so it's hard to solve the multi-routing, multi-input and output, multi-period production optimization problem by evolutionary algorithm.

There are some popular methods for dealing with the multi-objective optimization problem, such as goal programming method, ε constraint method and weighted coefficient method. For goal programming method, the objectives are converted into one equality constraint at least and the target is to minimize the weighted sum of all deviations [9]. In the absence of any precedence of ordering among the different objectives, the weighted coefficient method is a preferred alternative and applied in this paper to generate Pareto solution set. To obtain the effective solutions, the objective functions have to be normalized [10], F_1 is transformed to Γ_1,

$$\Gamma_1 = \frac{F_1(x)-F_1^{\min}}{F_1^{\max}-F_1^{\min}} \tag{23}$$

Similarly, F_2 is converted to Γ_2,

$$\Gamma_2 = \frac{F_2(x)-F_2^{\min}}{F_2^{\max}-F_2^{\min}} \tag{24}$$

where $F_1^{\min}$ and $F_1^{\max}$ are the minimum and maximum production cost, while $F_2^{\min}$ and $F_2^{\max}$ are the minimum and maximum inventory cost respectively. In this paper, the minimum and maximum productions are the solution of optimization model under the present constraints. The minimum inventory cost is the safety level inventory cost and the maximum inventory cost is the solution of optimization model in the present constraints. The normalized objective function is more sensitive to the weighted coefficients w_1 and w_2, and meanwhile, the impact from the relative size of two original objective function values has faded. Therefore, the optimization solutions are more reliable and reasonable. On the basis of presented multi-objective optimization strategy, the compromised solutions between production cost and inventory cost are obtained by different weighted coefficient values; consequently, Pareto curve for the multi-routing, multi-input and output, multi-period production optimization problem is acquired.

IV. CASE STUDY

The motivation for studying the multi-routing, multi-input and output, multi-period production optimization problem is a particular example in a steel company from China. The steel production process can be divided into several stages, including steel making, refining, continuous casting, hot rolling, pickling, cold rolling, heat treatment, etc. Each stage could also be split into different processes, which contain multiple facilities. The capacity of facilities utilized has an impact on each other during the processes, which forms the complex network flow routines of steel production as shown in figure1.

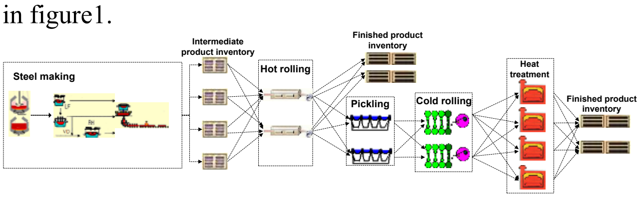

Figure1 network flow routines of steel production process

For the sake of planning and scheduling, the steel company groups steel production process into two sequential parts, including primary operations and finishing operations as shown in figure1[8]. Intermediate product inventory is considered as a decoupling inventory, which provides raw materials for rolling processes. The finishing operations vary depending on the variety of finished products being produced. At the request of order, the finished products contain hot-rolled products and cold-rolled products. Hot-rolled finished products is produced through hot rolling process, while cold-rolled finished products pass through both hot rolling process and cold rolling process. Facilities 1 and 2 in figure2 are hot rolling lines. In the case of pickling lines, facilities 3 and 4 given in figure2 deal the steel with hydrochloric acid to remove impurities from the surface of the steel. Then a protective oil coating is used and the steel passes through the cold rolling process. Facilities 5 and 6 are the cold rolling mills. The corresponding finished products performance can be achieved through different heat treatment methods. There are four heat treatment facilities to handle the steel. For the case study, 17 different routings may be used to produce the required finished products; however, each finished product can be produced from more than one raw material and also can be routed through more than one sequence of facilities.

Due to the characteristic and performance, the produced or purchased raw materials for producing finished products are grouped into different steel grades and dimensions. Clearly, the raw materials of a certain grade can only be used to produce the particular finished product on the requirement. Simultaneously, the finished products are categorized into different types on the basis of chemistry performance, the width and dimensions. An order for finished products consists of the quantity and the types to be produced. The order is assigned to a routing that produces particular type of steel. Some routings are available to produce a variety of dimensions of finished products, thus, an order could be allocated to any one of some different routings on demand.

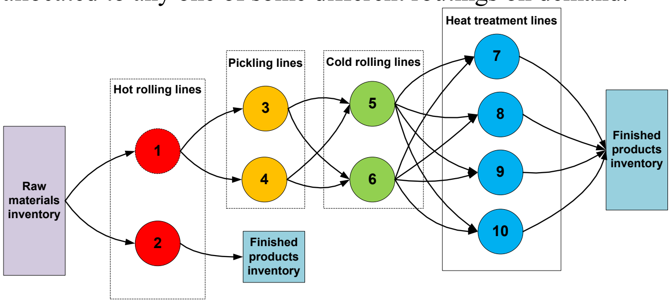

Figure2 finishing operations in the process of steel production

Recently, the steel company pursue the small quantities, quick production, high quality and low cost, which require that the processes and facilities should be improved to transform quickly and economically. The implication for solving the multi-routing, multi-input and output, multi-period production optimization problem is to minimize the production cost and inventory cost. In this case study, there are 6 types of raw materials for producing the finished products and 10 kinds of finished products required to be produced, where the values of dimension and gauge are index values. Table I and II give the supply quantity of raw materials and demand quantity respectively. The supply quantity is determined by the primary operations, which relate to steel making or material purchase. Demand quantity is given by production planning, which refers to the requirement of orders and delivery date of finished products.

TABLE I. SUPPLY QUANTITY OF RAW MATERIALS IN EACH TIME PERIOD

Raw material dimensions	**Supply quantity(ton)**			
k	$t=1$	$t=2$	$t=3$	$t=4$
1	96	94	98	96
2	88	90	92	94
3	80	78	76	74
4	50	52	54	56
5	45	46	47	48
6	60	80	70	30

TABLE II. DEMAND QUANTITY OF FINISHED QUANTITY IN EACH TIME PERIOD

Finished product gauges	**Demand quantity(ton)**			
i	$t=1$	$t=2$	$t=3$	$t=4$
1	60	90	70	0
2	58	85	65	78
3	44	101	97	65
4	79	96	0	85
5	89	39	57	65
6	77	65	58	47
7	64	84	30	78
8	52	46	91	92
9	56	79	93	80
10	0	93	64	51

The multi-objective optimization problem and corresponding solution strategy is studied. Two formulations with different constraints are discussed to analyze the influence on multiple routings choice in different time periods. Model 1 is the multi-routing, multi-input and output, multi-period production optimization formulation with facilities capacity restriction, and table III shows the 10 production facilities with their available capacities for producing finished products. For instance, facility $m=1$ is hot rolling line 1 which owns an available 400 tons capacity of these 10 types of required finished products per time period and the remainder of its capacity is applied to yield other steel products. Model 2 is the multi-routing, multi-input and output, multi-period production optimization formulation without capability constraint, indicating the facilities capabilities meet the requirement of these finished products and consisting of equations (2)~(15). Both of the formulations are MINLP problems, which are coded in the modeling environment of linear interactive general optimizer (LINGO) system and solved by the MINLP solver. A typical optimization run for Model 1 contains 4988 constrains, 3603 continuous variables and 4760 binary variables, whereas the similar formulation in Model 2 involves 4948 constrains, 4691 continuous variables and 4080 binary variables.

TABLE III. FACILITY AVAILABLE CAPACITY USED IN MODEL 1

Facility	Description	Capacity
1	Hot rolling line A	400
2	Hot rolling line B	270
3	Pickle line A	370
4	Pickle line B	390
5	Cold rolling line A	280
6	Cold rolling line B	160
7	Heat treatment A	200
8	Heat treatment B	330
9	Heat treatment C	130
10	Heat treatment D	150

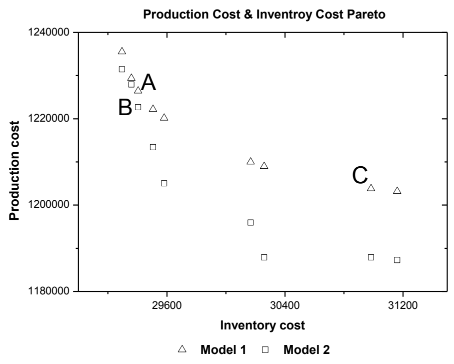

Figure3 production cost versus inventory cost Pareto curses for model 1 and model 2, respectively

The optimal solutions of the multi-routing, multi-input and output, multi-period production optimization problem for Model 1 and 2 generate the efficient frontier denoted as Pareto curse respectively, as presented in figure3. The conflict between the effects of the decision variables on the two objective functions, production cost and inventory cost, results in the optimum being the corresponding set of Pareto optimal solutions rather than a unique solution. The decision makers have to make a single choice among the whole Pareto points as the preferred solution for operation based on the demand satisfaction requirement. As the inventory cost rises, figure3 shows that the production cost reduces sharply and then stabilizes. The Pareto curse in Model 1 lies above the Pareto curse in Model 2, because Model 1 is a more restrictive case of Model 2, and thus, resulting in higher cost.

On each of these Pareto curses, one extreme point could be interpreted as one that yields the least production cost, while the other extreme point represents that generates the least inventory cost solution. Two points, point A and C in Model 1, are selected to analyze the solution performance. The various cost components of the total model cost, the inventory quantity, the quantity of utilized raw material and finished products quantity in every time period for point A and point C can be seen from the results shown in figure4 and figure5 respectively. Table IV shows the selected production routings in the situation of point A during every time period.

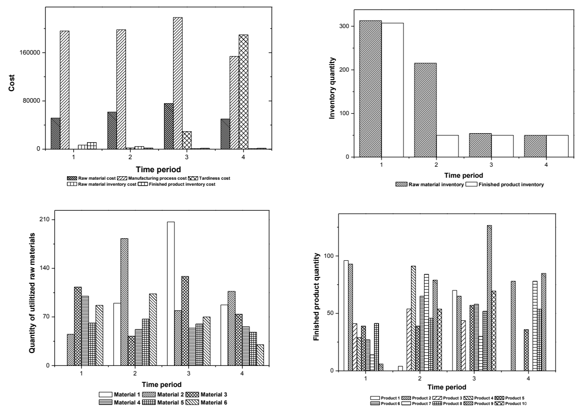

Figure4 total model cost, inventory quantity, utilized raw material quantity and finished products quantity in every time period for point A in model 1

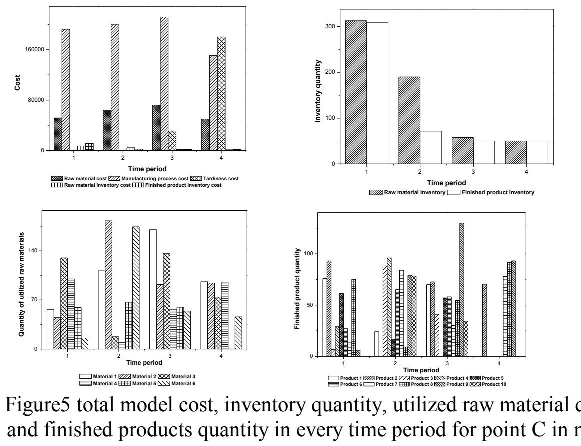

Figure5 total model cost, inventory quantity, utilized raw material quantity and finished products quantity in every time period for point C in model 1

TABLE IV. THE SELECTED PRODUCTION ROUTINGS FOR POINT A IN EVERY TIME PERIOD.

Time period	Finished products	Facility I	Facility II	Facility III	Facility IV	Utilized raw material
1	1	1	3	5	7	4
2	1	1	3	5	7	4
3	1	1	3	5	7	1
4	1	0	0	0	0	0

1	2	1	3	5	8	3
2	2	0	0	0	0	0
3	2	1	3	5	8	3
4	2	1	3	5	8	3
1	3	1	3	6	8	6
2	3	1	3	6	8	6
3	3	1	3	6	8	6
4	3	0	0	0	0	0
1	4	1	3	5	9	2
2	4	1	3	5	9	2
3	4	0	0	0	0	0
4	4	0	0	0	0	0
1	5	1	4	6	8	3
2	5	1	4	6	8	3
3	5	1	4	6	8	3
4	5	1	4	6	8	3
1	6	1	4	5	10	5
2	6	1	4	5	10	5
3	6	1	4	5	10	5
4	6	0	0	0	0	0
1	7	1	3	5	9	2
2	7	1	3	5	9	2
3	7	1	3	5	9	2
4	7	1	3	5	9	2
1	8	1	3	6	8	6
2	8	1	4	6	7	4
3	8	1	4	6	7	4
4	8	1	4	6	7	4
1	9	2	0	0	0	3
2	9	2	0	0	0	3
3	9	2	0	0	0	1
4	9	2	0	0	0	1
1	10	0	0	0	0	0
2	10	2	0	0	0	2
3	10	2	0	0	0	2
4	10	0	0	0	0	0

From these figures, it is observed that there is a tradeoff between production cost and inventory cost in steel production process. Under the production requirements, with the growing of production cost, the inventory cost presents a corresponding decrease. There is a high production cost and low inventory for point A. In contrast, point C reduces the production cost but increase inventory cost a little. Due to the priority of reducing production cost and inventory cost considered by decision-makers, the quantity of utilized raw materials for point A is vastly different from that for point C. Simultaneously, in order to meet the requirements of order demand and maintain the stability of production process, each finished product is produced on the optimal routing from raw materials during every time period, as shown in table IV. For instance, finished product 1 is produced on routing 1 by raw material 4 from time period 1 to 2 and raw material 1 in time period 3. That is , this product is processed through facility $m=1$, Hot rolling line A, then $m=3$, Pickle line A, and $m=5$, Cold rolling line A, and after a time in the cold roll inventory, it goes to $m=7$, Heat treatment A where it is completed and sent to the finished products inventory. However, due to the process requirement, finished product 9 and 10 choose routing 17 during production period. That is, these products are produced through facility $m=2$, Hot rolling line B, and then sent to the finished products inventory. Specific production routing selected for the other products were generated in production process but are not described here for the sake of brevity. Considering the actual constraints and requirements, decision-makers balance the relation between production cost and inventory cost in steel production process and select one operating point to get the minimum cost.

V. Conclusion

The present study addresses the challenge of selecting the appropriate routing and optimizing the manufacturing routing in steel production process. A practical and validated model is established to solve the multi-routing, multi-input and output, multi-period production optimization problem, which focuses on minimizing the production cost and inventory cost simultaneously under production and order requirements. With the multi-objective optimization strategy, the efficient Pareto curve is obtained to describe the relation between production cost and inventory cost of steel finished products. The appropriate routing is determined under the solution selected from the Pareto curve. This multi-objective optimization strategy will reduce the production cost and inventory cost, and improve the production process to increase the profit. Furthermore, this optimization strategy could be used in other similar production processes with multi-routing, multi-input and output and multi-period.

References

[1] M. Vanhoucke and D. Debels. A finite-capacity production scheduling procedure for a Belgian steel company. *International Journal of Production Research*, vol.47, no.4, pp. 561-584,2009.

[2] Lixin Tang, Jiyin Liu, Aiying Rong and Zihou Yang. A review of planning and scheduling systems and methods for integrated steel production. *European Journal of Operational Research*, vol.133, no.1, pp.1-20, 2001.

[3] Simone Zanoni, Lucio Zavanella. Model and analysis of integrated production-inventory system: The case of steel production. *International Journal of Production Economics*, pp.197-205, 2005.

[4] Shixin Liu, Jiafu Tang, Jianhai Song. Order-planning model and algorithm for manufacturing steel sheets. *International Journal of Production Economics*, vol.1, no.100, pp.30-43, 2006.

[5] M.P. Biswal and S. Acharya. Multi-choice multi-objective mathematical programming model for integrated production planning: a case study. *International Journal of Systems Science*, pp.1-15, 2012.

[6] Tadeusz Sawik. Multi-objective master production scheduling in make-to-order manufacturing. *International Journal of Production Research*, vol.45, no.12, pp.2629-2653, 2007.

[7] Shaya Sheikh. Multi-objective flexible flow lines with due window, time lag, and job rejection. *International Journal of Advanced Manufacturing Technology*, pp.1-11, 2012.

[8] J. Miltenburg. Production planning problem where products have alternative routings and bills-of-material. *International Journal of Production Research*, vol.39, no.8, pp.1755-1775, 2010.

[9] Miettinen, K. Nonlinear Multi-objective Optimization. *Kluwer Academic Pubishers: Boston*, 1999.

[10] Marler R T, Arora J S. Survey of multi-objective optimization methods for engineering. *Structural and Multidisciplinary Optimization*, vol.26, no.6, pp.369-395, 2004.