Multi-Stage Multi-Period Production Planning in Wire and Cable Industry

Mahnaz Hosseinzadeh, Shaghayegh Rezaee Amiri

Abstract—This paper presents a methodology for serial production planning problem in wire and cable manufacturing process that addresses the problem of input-output imbalance in different consecutive stations, hoping to minimize the halt of machines in each stage. To this end, a linear Goal Programming (GP) model is developed, in which four main categories of constraints as per the number of runs per machine, machines' sequences, acceptable inventories of machines at the end of each period, and the necessity of fulfillment of the customers' orders are considered. The model is formulated based upon on the real data obtained from IKO TAK Company, an important supplier of wire and cable for oil and gas and automotive industries in Iran. By solving the model in GAMS software the optimal number of runs, end-of-period inventories, and the possible minimum idle time for each machine are calculated. The application of the numerical results in the target company has shown the efficiency of the proposed model and the solution in decreasing the lead time of the end product delivery to the customers by 20%. Accordingly, the developed model could be easily applied in wire and cable companies for the aim of optimal production planning to reduce the halt of machines in manufacturing stages.

Keywords—Serial manufacturing process, production planning, wire and cable industry, goal programming approach.

I. INTRODUCTION

TODAY, because of the rich copper reserves and the pull and demand of neighboring countries to wire and cable, the wire and cable industry has become one of the key popular industries in Iran. However, the complexity of the production process, as well as the instability of the copper market, as the main material of its production, and sometimes of granular materials, have caused problems for the industry in terms of planning orders and sequencing the production stages. Besides, due to the volatility of copper prices, it is not economical to stock the final products or raw materials. The complexity of production and the need for sequencing in the production line often result in breaks in machines' work and it in turns leads to delivery delays to customers [1]. So, the industry needs very tangible production planning. Classical production planning models determine the production plan so as to minimize the cost or maximize the profit of the system, assuming that customers' demand must be satisfied when capacity is available [2]. The multi-stage production system having one or more machines at each stage takes inputs from the preceding stage and produce outputs which, by itself,

become inputs to the machines in the next stage [3]. In such a system, the intermediate and end product rates of production could vary due to setting of in-process variables at a specific stage and also the interdependency between stages [4]. Imbalanced input–output relations between the consecutive machines may cause halt in the operation of the production line; thus, they lead to some amount of idle time in the machines and they thereby affect the production target at the end [3].

Many researches have endeavored to develop mathematical models to optimize the production line performance in a serial multi-stage process. For example, Bera and Mukherjee [4] developed a solution approach for a typical serial multistage problem. Their approach integrated a modified desirability function, and they used an ant colony-based meta-heuristic search strategy to find the best solution. Gupta and Mohanty [3] provided a methodology based on fuzzy logic to hold the desired balance between inputs and outputs of intermediate and final stages of a serial system in a multi-stage production planning problem. Lu et al. [5] posed a MILP model to plan the production lots of a multi-product multi-stage production system considering lead time in various forms. They implemented the model on a rolling horizon basis and applied it into a real case problem. Torkaman et al. [6], [7] study multi-stage multi-product multi-period capacitated production planning problem with sequence dependent setups in closed-loop supply chain. To this end, they formulated a mixed-integer programming (MIP) problem and to solve the model that they utilized four MIP-based heuristics named non-permutation and permutation heuristics, using rolling horizon.

In this paper, we are to develop a GP problem to model the production process of the wire and cable industry in Iran in order to minimize the idle time in the machines considering the balanced input–output relation between the consecutive stages.

The remainder of this paper is organized as follows. The case study company and its production process are addressed in Section II. In Section III, the research methodology is discussed. The GP model is presented in Section IV, and the computational results are presented in this section. The conclusion and future research are mentioned in Section V.

II. THE CASE STUDY COMPANY

ZiaGostar engineering company under the commercial name of IKOTAK is one of the important suppliers of wire and cable for oil and gas and automotive industries in Iran. Currently, the group can convert 600 tons of copper and 600 tons of aluminum annually into different types of wires and

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cables in accordance with international standards including VDE Germany, BS United Kingdom and IEC.

The company works with a multi-stage production process consisting of six stages with one or more machines in each stage. The production process starts with input of raw material to the Rod machine in the first stage and sequentially proceeds to the Coating Extruder machine in the final stage, where finished product is produced. Fig. 1 shows the multi-stages process of production in the case study company. Further, what is done by different machines in the process is described.
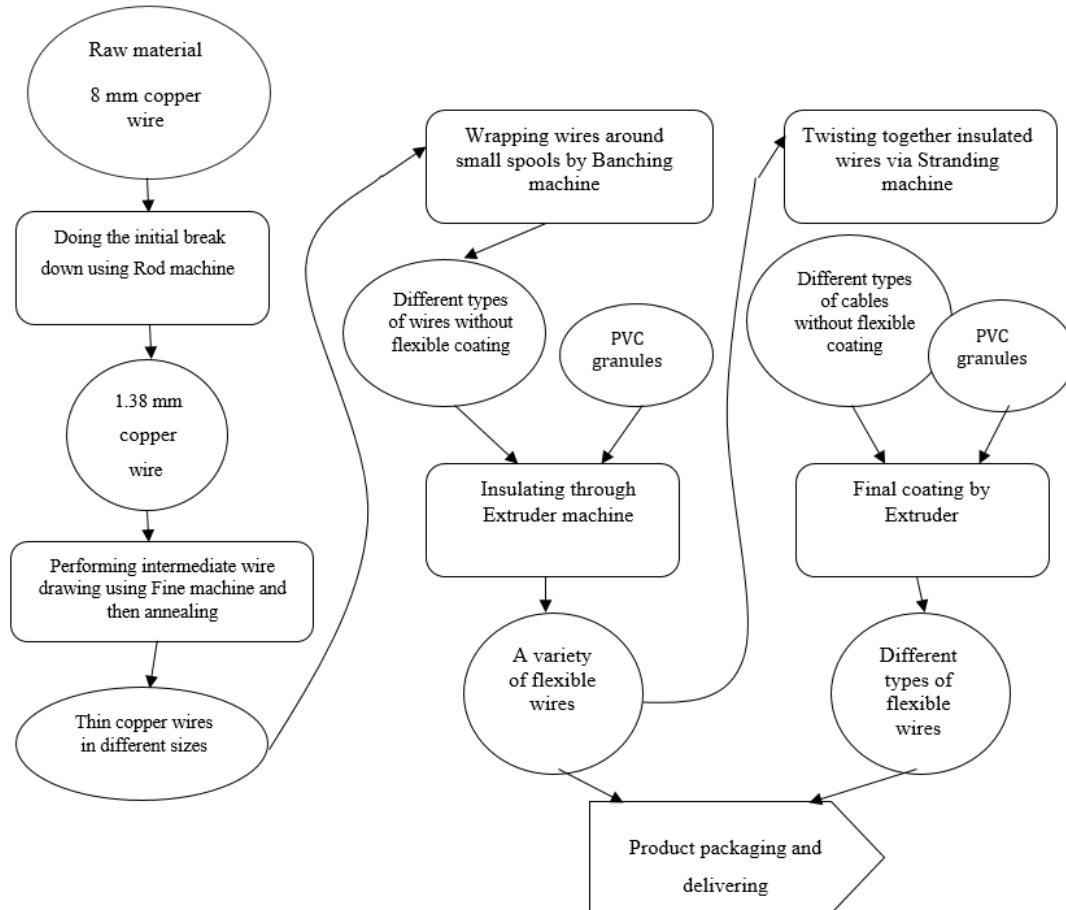
Fig. 1 The multi-stages process of production in the IKO TAK Company

Rod machine: This machine is used in the first stage of the joinery, in which the 8-mm copper wire is converted into 1.38 mm wire.

Fine machine: This machine is used in the second stage of the joinery, using which the 1.38-mm copper wire is turned into thinner wire according to the customers' requests.

Annealing machine: In this machine, the thin-walled wire is placed under heat to form annealing, which means that the softness increases, so that it can easily be formed without breaking.

Banching Machine: After annealing, the wires are wrapped around small spools, and then they are placed on the Banching machine. This rotates the wires in a number of spools.

Insulating Extruder machine: The sticky wires are again placed on a reel and placed at the top of the Extruder machine, then the granular material tank is filled with the color and the appropriate amount of PVC granules. These granular materials are heated and melted, and injected into the mold, where bundled wires flow through it. These materials are taken as a layer of veneer around the wire and then move into a cold water pool to cool, which is said to be insulated.

Stranding machine: It is almost identical to Extruder machine, but slightly larger, in which the insulated wires are twisted together to become cable after coating.

Coating Extruder machine: It is the same as the Insulating Extruder machine, but its mold is larger and in which the strand wires are coated.

III. RESEARCH METHODOLOGY

The purpose of the current study is to determine the optimal number of runs for each machine in different stations as well as the product inventory at the end of each period for each station hoping to maintain balanced input–output relation between the consecutive stages. A GP problem is developed to model the production process with the aim of minimizing the idle time in the machines. In the modeling process, four categories of constraints are considered, which are:
1- Constraints as to the number of runs per machine.
2- Machines' sequence limitations.

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TABLE I
INDICES, VARIABLES, AND PARAMETERS APPLIED IN THE MODEL

Indices	
$t = 1, \dots, T$	The period in which production takes place
$i = 1, \dots, I$	The type of thin wire that comes out of the Fine machine.
$d = 1, \dots, D$	The number of Fine machines in station 2.
$e = 1, \dots, E$	The number of Banching machines in station 3.
$f = 1, \dots, F$	The number of Insulating Extruder machines in station 4.
$g = 1, \dots, G$	The number of Stranding machines in station 5.
$h = 1, \dots, H$	The number of Coating Extruder machines in station 6.
$j = a, b, c, d, e$	The type of open wires that come out of the Banching machine
$p = r, b, y, g, o, p$	The color of wire insulation used in the initial coating step.
$m = 1, \dots, M$	The number of wires with an initial coating that are twisted together.
$l = 1, \dots, L$	Cable types produced by the Stranding machine.
$s = 1, \dots, S$	Work stations
Decision variables	
$x_1(t)$	The number of Rod machine's runs to produce wire 1.38 mm during period t
$x_{id}(t)$	The number of runs for the d_{th} Fine machine to produce thin wire type i during period t
$x_{je}(t)$	The number of runs for the e_{th} Banching machine to produce open wire type j during period t
$x_{pjf}(t)$	The number of runs for the f_{th} Insulating Extruder machine to produce wire type j coated with color p during period t
$x_{lgm}(t)$	The number of runs for the g_{th} Stranding machine to produce cable l from m number of wire j with color p in period t
$x_{lh}(t)$	The number of runs for the h_{th} Extruder machine to produce cable l with the final coating in period t
y_1^+	The overtime of Rod machine at workstation 1 in period t
y_1^-	The idle time of Rod machine at workstation 1 in period t
y_{2d}^+	The overtime of the d_{th} Fine machine at workstation 2 in period t
y_{2d}^-	The idle time of the d_{th} Fine machine at workstation 2 in period t
y_{3e}^+	The overtime of the e_{th} Banching machine at workstation 3 in period t
y_{3e}^-	The idle time of the e_{th} Banching machine at workstation 3 in period t
y_{4f}^+	The overtime of the f_{th} Insulating Extruder machine at workstation 4 in period t
y_{4f}^-	The idle time of the f_{th} Insulating Extruder machine at workstation 4 in period t
y_{5g}^+	The overtime of the g_{th} Stranding machine at workstation 5 in period t
y_{5g}^-	The idle time of the g_{th} Stranding machine at workstation 5 in period t
y_{6h}^+	The overtime of the h_{th} Coating Extruder machine at workstation 6 in period t
y_{6h}^-	The idle time of the h_{th} Coating Extruder machine at workstation 6 in period t
$I(t)$	Rod machine's inventory at the end of period t
$I_i(t)$	The inventory of thin wire type i at the end of period t
$I_j(t)$	The inventory of open wire type j at the end of period t
$I_{pj}(t)$	The inventory of wire j with insulating color p at the end of period t
$I_{lm}(t)$	The inventory of cable l which consists of m wire type j at the end of period t
$I_l(t)$	The inventory of cable l with final coating at the end of period t.
$CO_{pj}(t)$	The number of coils made of wire type j with insulating color p produced in period t.
$CO_l(t)$	The number of coils made of cable type l produced in period t.
$CO_{pj}(t-1)$	The inventory for coils of wire type j with insulating color p at the beginning of period t.
$CO_l(t-1)$	The inventory for coils of cable type l at the beginning of period t.

q_{pj}	The amount of wire type j with color p devoted to serve the customers' needs.
Parameters	
v_1	The amount of wire 1.38 mm produced per run of Rod machine.
v_i	The amount of wire type i produced per run of Fine machine.
v_j	The amount of wire type j produced per run of Banching machine.
v_{lm}	The amount of cable l which consists of m wire type j produced per run of Insulating Extruder machine
v_l	The amount of cable l produced per run of Coating Extruder machine
$H_s(t)$	The machine's availability time at workstation s in period t
$U_s(t)$	Machines inventory capacity in workstation s at the end of period t.
$DE_l(t)$	The demand of cable l in period t.
$DE_{pj}(t)$	The demand of wire type j with insulating color p in period t.
α_{ji}	Number of wire i strings (spools) required for the production of wire type j

3- Restrictions on the acceptable inventory at the end of each period.

4- Constraints as regards the fulfillment of the orders.

The model is run and solved in GAMS software, and the optimal solutions for decision variables are obtained.

IV. MATHEMATICAL FORMULATION OF THE GP MODEL

Table I represents indices, variables, and parameters used to describe the production process of the wire and cable manufacturing company.

Four categories of constraints mentioned in Section III are presented in this section in details. It must be noted that each run for each machine takes an hour; accordingly, each run is equal to one hour.

A. Constraints as to the Number of Runs per Machine

In these constraints, the number of permitted implementations of machines at each workstation is expressed.

The limitation of runs for Rod machine is presented in (1).

$$x_1(t) + y_1^- - y_1^+ = H_1(t) \qquad (1)$$

where H_1 is the Rod machine's available time or the maximum allowed number of runs for Rod machine during production period t, and y_1^- and y_1^+ represent the idle time and overtime of Rod machine at period t, respectively.

Equation (2) shows the run numbers limitation as to Fine machine.

$$\sum_{i=1}^{I} x_{id}(t) + y_{2d}^- - y_{2d}^+ = H_2(t) \quad for \; d = 1, \dots, D \quad (2)$$

where H_2 is the Fine machine's available time or the maximum allowed number of runs for Fine machine during production period t, and y_{2d}^- and y_{2d}^+ represent the idle time and overtime of the d_{th} Fine machine at period t, respectively.

The run numbers limit as regards Banching machine is as presented in (3).

$$\sum_{j=1}^{J} x_{je}(t) + y_{3e}^- - y_{3e}^+ = H_3(t) \quad for \; e = 1, \dots, E \quad (3)$$

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where H_3 is the Bancing machine's available time or the maximum allowed number of runs for Bancing machine during production period t, and y_{3e}^- and y_{3e}^+ represent the idle time and overtime of the e_{th} Bancing machine at period t, respectively.

In (4), the run numbers limit of the Insulating Extruder machine is presented.

$$\sum_{j=1}^{J} \sum_{p=1}^{P} x_{pjf}(t) + y_{4f}^- - y_{4f}^+ = H_4(t) \ \ for \ f = 1, \dots, F \quad (4)$$

where H_4 is the Insulating Extruder machine's available time or the maximum allowed number of runs for Insulating Extruder machine during production period t, and y_{4f}^- and y_{4f}^+ represent the idle time and overtime of the f_{th} Insulating Extruder machine at period t, respectively.

The limitation of runs for Stranding machine is posed in (5).

$$\sum_{m=1}^{5} \sum_{l=1}^{L} x_{lgm}(t) + y_{5g}^- - y_{5g}^+ = H_5(t) \ \ for \ g = 1, \dots, G \quad (5)$$

where H_5 is the Stranding machine's available time or the maximum allowed number of runs for Stranding machine during production period t, and y_{5g}^- and y_{5g}^+ represent the idle time and overtime of the g_{th} Stranding machine at period t, respectively.

In (6), the run numbers limit as for Coating Extruder machine is shown.

$$\sum_{l=1}^{L} x_{lh}(t) + y_{6h}^- - y_{6h}^+ = H_6(t) \quad for \ h = 1, \dots, H \quad (6)$$

where H_6 is the Coating Extruder machine's available time or the maximum allowed number of runs for Coating Extruder machine during production period t, and y_{6h}^- and y_{6h}^+ represent the idle time and overtime of the h_{th} Coating Extruder machine at period t, respectively.

B. Machines' Sequence Constraints

These limitations are to observe the machines' sequences and to balance the inputs and outputs of sequential machines.

Equation (7) shows that the output of Rod machine is taken as the input to Fine machines.

$$v_1 x_1(t) + I(t-1) - I(t) = \sum_{d=1}^{D} \sum_{i=1}^{I} v_i x_{id}(t) \quad (7)$$

Based on (8), the outputs of the Fine machines are to reach a certain amount to be used by Banching machines for production wire type j, identified by α_{ji}. Therefore, whenever the output of all Fine machines from a specific wire i reaches the number of α_{ji}, it could be the input of Banching machines to produce wire type j.

$$\sum_{d=1}^{D} v_i x_{id}(t) + I_i(t-1) - I_i(t) = \sum_{e=1}^{E} \alpha_{ji} v_j x_{je}(t)$$
$$for \ i = 1, \dots, I \quad and \ j = 1, \dots, J \quad (8)$$

Equation (9) denotes that the output of Banching machine is directly injected into Insulated Extruder machine, in which the wire is produced with different insulating colors.

$$\sum_{e=1}^{4} v_j x_{je}(t) - I_j(t-1) - I_j(t) = \sum_{f=1}^{F} \sum_{p=1}^{P} v_{pj} x_{pjf}(t)$$
$$for \ j = 1, \dots, J \quad (9)$$

Based upon (10), the output of Insulating Extruder machine is used even as the final product to satisfy customer demand or as an input of Stranding machine in which two, three, four, or five (m = 2,3,4,5) wires are welded together to produce uncoated cables.

$$\sum_{f=1}^{F} \sum_{p=1}^{P} \sum_{j}^{J} v_j x_{pfj}(t) + \sum_{p=1}^{P} \sum_{j}^{J} I_{pj}(t-1) - \sum_{p=1}^{P} \sum_{j}^{J} I_{pj}(t) =$$
$$\sum_{p=1}^{P} \sum_{j}^{J} q_{pj}(t) + \sum_{m}^{M} \sum_{g=1}^{G} \sum_{l=1}^{PJ} m v_{lm} x_{lgm}(t) \quad (10)$$

where, $l = 1, \dots, PJ$ which denotes cable l is corresponding to wire j with color p.

According to (11), the output of the Stranding device is identified as the input of the Coating Extruder machine, which produces cable type l as the final product to be provided to the customers.

$$\sum_{m}^{M} \sum_{g=1}^{G} \sum_{l=1}^{PJ} v_{lm} x_{lgm}(t) + \sum_{m=1}^{M} \sum_{l}^{PJ} I_{lm}(t-1) -$$
$$\sum_{m=1}^{M} \sum_{l}^{PJ} I_{lm}(t) = \sum_{h=1}^{H} \sum_{l}^{PJ} v_l x_{lh}(t) \quad (11)$$

C. End-of-Period Inventory Constraints

These categories of constraints in (12)-(17) show the acceptable amount of inventories for each machine at the end of each production period.

$$I(t) \leq U_1(t) \quad (12)$$

$$I_i(t) \leq U_2(t) \quad (13)$$

$$I_j(t) \leq U_3(t) \quad (14)$$

$$\sum_{p=1}^{P} \sum_{j}^{J} I_{pj}(t) \leq U_4(t) \quad (15)$$

$$\sum_{m=1}^{M} \sum_{l}^{PJ} I_{lm}(t) \leq U_5(t) \quad (16)$$

$$I_l(t) \leq U_6(t) \quad (17)$$

where $l(t), l_i(t), l_j(t), l_{pi}(t), l_{lm}(t), l_l(t)$ respectively show the inventories of Rod, Fine, Banching, Insulating Extruder, Standing, and Coating Extruder at the end of period t, and $U_1(t), U_2(t), U_3(t), U_4(t), U_5(t), U_6(t)$ are the allowed amount of inventory for each machine, respectively.

D. Constraints as regards the fulfillment of the orders

These categories of constraints denote the limitations of the order fulfillment. Orders are in the form of 100-meter coils in two types of wire and cable.

The number of 100-meter coils of wire j with color p in period t is calculated as in (18).

$$q_{pj}(t) = 100 CO_{pj}(t) \quad for \ p = 1, \dots, P \quad and \ j = 1, \dots, J \quad (18)$$

Equation (19) represents the fulfilment of demand for wire j with color p in period t.

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$$CO_{pj}(t) + CO_{pj}(t-1) \geq DE_{pj}(t)$$
$$for \; p = 1, \dots, P \quad and \; j = 1, \dots, J \qquad (19)$$

The number of 100-meter coils of cable l in period t is mentioned in (20).

$$\sum_{h=1}^{H} v_{lh} x_{lh}(t) = 100 CO_l \qquad (20)$$

Equation (21) denotes the way of serving demand for wire j with color p in period t.

$$CO_l + CO_l(t-1) \geq DE_l(t) \qquad for \; l = 1, \dots, L \qquad (21)$$

The general parametric form of the proposed GP model is presented in model (22).

$$Min \; Z = y_1^- + \sum_{d=1}^{D} y_{2d}^- + \sum_{e=1}^{E} y_{3e}^- + \sum_{f=1}^{F} y_{4f}^- + \sum_{g=1}^{G} y_{5g}^- + \sum_{h=1}^{H} y_{6h}^- \qquad (22)$$

Subject.to

$$x_1(t) + y_1^- - y_1^+ = H_1(t)$$
$$\sum_{i=1}^{I} x_{id}(t) + y_{2d}^- - y_{2d}^+ = H_2(t) \quad for \; d = 1, \dots, D$$
$$\sum_{j=1}^{J} x_{je}(t) + y_{3e}^- - y_{3e}^+ = H_3(t) \quad for \; e = 1, \dots, E$$
$$\sum_{j=1}^{J} \sum_{p=1}^{P} x_{pjf}(t) + y_{4f}^- - y_{4f}^+ = H_4(t) \; for \; f = 1, \dots, F$$
$$\sum_{m=1}^{5} \sum_{l=1}^{L} x_{lgm}(t) + y_{5g}^- - y_{5g}^+ = H_5(t) \; for \; g = 1, \dots, G$$
$$\sum_{l=1}^{L} x_{lh}(t) + y_{6h}^- - y_{6h}^+ = H_6(t) \quad for \; h = 1, \dots, H$$
$$v_1 x_1(t) + I(t-1) - I(t) = \sum_{d=1}^{D} \sum_{i=1}^{I} v_i x_{id}(t)$$
$$\sum_{d=1}^{D} v_i x_{id}(t) + I_i(t-1) - I_i(t) = \sum_{e=1}^{E} \alpha_{ji} v_j x_{je}(t)$$
$$for \; i = 1, \dots, I \quad and \; j = 1, \dots, J$$
$$\sum_{e=1}^{4} v_j x_{je}(t) - I_j(t-1) - I_j(t) =$$
$$\sum_{f=1}^{F} \sum_{p=1}^{P} v_{pj} x_{pjf}(t) \qquad for \; j = 1, \dots, J$$
$$\sum_{f=1}^{F} \sum_{p=1}^{P} \sum_{j}^{J} v_j x_{pfj}(t) + \sum_{p=1}^{P} \sum_{j}^{J} I_{pj}(t-1) - \sum_{p=1}^{P} \sum_{j}^{J} I_{pj}(t) =$$
$$\sum_{p=1}^{P} \sum_{j}^{J} q_{pj}(t) + \sum_{m}^{M} \sum_{g=1}^{G} \sum_{l=1}^{PJ} m v_{lm} x_{lgm}(t)$$
$$\sum_{m}^{M} \sum_{g=1}^{G} \sum_{l=1}^{PJ} v_{lm} x_{lgm}(t) +$$
$$\sum_{m=1}^{M} \sum_{l}^{PJ} I_{lm}(t-1) - \sum_{m=1}^{M} \sum_{l}^{PJ} I_{lm}(t) = \sum_{h=1}^{H} \sum_{l}^{PJ} v_l x_{lh}(t)$$
$$I(t) \leq U_1(t)$$
$$I_i(t) \leq U_2(t)$$
$$I_j(t) \leq U_3(t)$$
$$\sum_{p=1}^{P} \sum_{j}^{J} I_{pj}(t) \leq U_4(t)$$
$$\sum_{m=1}^{M} \sum_{l}^{PJ} I_{lm}(t) \leq U_5(t)$$
$$I_l(t) \leq U_6(t)$$
$$q_{pj}(t) = 100 CO_{pj}(t) \quad for \; p = 1, \dots, P \quad and \; j = 1, \dots, J$$
$$CO_{pj}(t) + CO_{pj}(t-1) \geq DE_{pj}(t)$$
$$for \; p = 1, \dots, P \quad and \; j = 1, \dots, J$$
$$\sum_{h=1}^{H} v_{lh} x_{lh}(t) = 100 CO_l$$
$$CO_l + CO_l(t-1) \geq DE_l(t) \quad for \; l = 1, \dots, L$$

All variables are non-negative.

The model was solved using the actual data of IKO TAK Company in the GAMS software.

There are one Rod machine, six Fine machines ($d = 1, \dots, 6$), four Banching machines ($e = 1, \dots, 4$), two Insulating Extruder machines ($f = 1,2$), one Stranding machine ($g = 1$), and two Coating Extruder machines ($h = 1,2$) in IKO TAK Company. The main objective is to minimize the idle times of machines, which is presented in (23):

$$Min \; Z = y_1^- + \sum_{d=1}^{6} y_{2d}^- + \sum_{e=1}^{4} y_{3e}^- + \sum_{f=1}^{2} y_{4f}^- + y_{51}^- + \sum_{h=1}^{2} y_{6h}^- \qquad (23)$$

The optimal solution obtained for each period $t = 1$ month and two shift works per day, is presented in Table II.

TABLE II
OPTIMAL SOLUTION FOR IKO TAK COMPANY

$y_1^- = 67$	$y_{32}^- = 88$
$y_{21}^- = 0$	$y_{33}^- = 96$
$y_{22}^- = 0$	$y_{34}^- = 94$
$y_{23}^- = 0$	$y_{41}^- = 74$
$y_{24}^- = 0$	$y_{42}^- = 96$
$y_{25}^- = 0$	$y_{51}^- = 92$
$y_{26}^- = 0$	$y_{61}^- = 92$
$y_{31}^- = 86$	$y_{62}^- = 96$

V. CONCLUSION

A serial manufacturing system generally consists of multiple and different processing stages which are aligned sequentially to produce a specific final product [4]. In a sequential production process, the input material passes through successive processing stages which are ordered and required to manufacture the final product. The interdependency between the stages often results in misbalance of input–output between consecutive machines; thus, a timeout could occur during the process, causing to getting away from the production goals. So, an accurate production planning is needed to enhance the competitiveness of the companies. This paper presented a GP model for serial multi-stage manufacturing systems in wire & cable industry for data adopted from IKO TAK Company, an important supplier of wire and cable for oil& gas and automotive industries in Iran, so as to minimize the idle time in the machines.

The proposed GP model determined the optimal number of runs for each machine in different stations as well as the product inventory at the end of each period for each station to minimize the idle times of machines in each stage.

The model solution has applied in production line of the company for six months and it has shown 20% reduction in the time of final product delivery to the customers.

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