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OPTIMAL SHUTDOWN SCHEDULE OF HEAT TREATMENT FURNACE – A CASE

by

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Abstract

This paper deals with optimal shutdown analysis of a 250 kg/h heat-treatment furnace in a manufacturing plant. The parts undergo heat treatment before going through a sequence of manufacturing operations. At the time of the study that was carried out a few years ago, there was an excess capacity available at the heat-treatment furnace, the average capacity utilization of the furnace being about 75%. The company followed the practice of shutting down the furnace during the slack times in order to save energy. There was no scientific basis for deciding the shutdown schedule for the heat-treatment furnace. The basic consideration for shutting down the furnace was to ensure that the downstream machines should not be starved of the heat-treated parts. In this paper, the optimal shutdown schedule of the furnace has been derived by minimizing the combined cost of energy and the heat-treated inventory holding cost so that the post-furnace built-up inventory satisfies the downstream demand in a plan period.

Keywords: Heat treatment furnace, Optimal shutdown schedule, Total energy and inventory holding cost, Heat-treatment cycle

INTRODUCTION

This study has been carried out in a manufacturing company, where the parts undergo heat treatment before going through a sequence of manufacturing operations. Heat-treatment is done in this company in a 250 kg/h heat treatment furnace. There was an excess capacity available at the heat-treatment furnace, the capacity utilization of the furnace being about 75 %. The practice followed in the company was to shut down the furnace during the slack times in order to save energy. There was no scientific basis for deciding the shutdown schedule for the heat-treatment furnace.

Heat treatment, being a prerequisite upstream operation for manufacturing the parts, the basic consideration for shutting down the furnace is to ensure that the downstream machines should not be starved of the heat-treated parts. In this paper we show that the furnace can be shut down judiciously so as to minimize the combined cost of energy and heat-treated inventory holding cost such that the post-furnace built-up inventory satisfies the downstream demand in the plan period.

The rated loads at different stages of the 250 kg/h furnace are shown in Table 1. As shown in Table 1, the total load for the furnace is 360 kW, whereas the total connected load is 400 kW. When the furnace is loaded with material, it takes only 40 % of 400 kW, which is only 160 kW. If the furnace is not loaded with material, then it takes 30 % of the connected load (i.e., only 120 kW). Thus, one can say that much of the power is consumed for the maintenance of the temperatures of the furnace.

Table 1: Rated Loads for Various Furnace Operations

Operation	Rated Load (kW)
Austenitising	200
Quenching	60
Tempering	90
Hot-water tank	10
Others[1]	40
Total:	400

[1] "Others" include the power for stirrers, blowers, and cranes, etc.

If the furnace is shutdown and then started again, it takes the total connected load of 400 kW before reaching the normal operating temperatures. The times taken for different periods of the shutdown are shown in Table 2. The variation in these times is because of the extent of cooling down of the brick-linings of the furnace along with the solidification of the salt.

Table 2: Days and Times of Shutdown

Number of Days of Shutdown (day)	Time for Which Total Connected Load Is Taken (h)
1	8
2 – 4	10
>= 5	12

Chloride Dissolution

For preventive maintenance, the furnace undergoes chloride dissolution on every seventh day of operation. So production cannot continue for more than six days at a stretch. For technical reasons, it is advisable to shut down the furnace for a longer period rather than shutting it down very frequently for a smaller duration. On a chloride dissolution day, there cannot be any production. Therefore, it is possible to get maximum advantage when the shutdown time follows the chloride dissolution time.

The process of chloride dissolution consists of austenitising, quenching, tempering, and hot water bath. On a chloride dissolution day, the power to the auzetnitsing zone can be switched off after the cleaning, and power to the quenching zone can be switched off after the filter change is completed provided it is known that a shutdown would follow the next day. The austenitising zone is maintained for 21.67 h at 60 kW power consumption, and the quenching zone is maintained for four hours at 18 kW power consumption.

The Downstream Processes

The heat-treatment furnace feeds the face grinding machines, which, in turn, feeds the outer diameter grinding machines. The grinding machines feed the modules. As the stock-out costs associated with the modules are very high, it is necessary to ensure that there is no stock-out at the modules. In fact any stock-out at any of the grinding machines is also very costly. Therefore, a decision to put off the furnace to save energy must consider the availability of sufficient material at the downstream machines. This condition can be satisfied if adequate quantity of inventory is built up after heat-treatment so that the inventory is sufficient to feed the grinding machines and so the modules. Building up inventory, however, is also costly. So, there is a need to make a tradeoff between the energy and the inventory, by minimizing the total cost of energy and inventory built-up after heat-treatment.

Considerations for Optimal Shutdown Decisions

To find the optimal shutdown schedule, one must make the following considerations:

1. The production periods of the heat-treatment should be such that the demand at the downstream modules is met.
2. The production run time for the furnace has to be less than 6 days, because the preventive maintenance activities are carried out on the furnace on every seventh day coinciding with the chloride dissolution operation.
3. The furnace consumes only 30 % of the total connected load when maintained without material, whereas, in a fresh start up, it takes the full connected load for the entire period of shutdown.
4. The total cost of energy and the cost incurred due to the inventory build up after heat-treatment has to be minimized.

Optimization Models

The problem is formulated assuming that the rate of demand from the downstream machine and rate of production (in terms of weight) at the furnace remain constant in a plan period.

Three non-linear programming models are developed in this paper. These models consider the process of heat-treatment to occur in cycles, each cycle consisting of four phases: start-up, production, chloride dissolution, and shutdown. The objective of the analysis is to minimize the sum of the energy and inventory holding cost per unit time.

Model 1

Model 1 assumes that chloride dissolution should be immediately followed by a shutdown. The basic assumption for the analysis is that the rate of demand from the downstream machine and the rate of production at the furnace remain constant during a plan period. The inventory and the power curves are shown in Fig. 1.

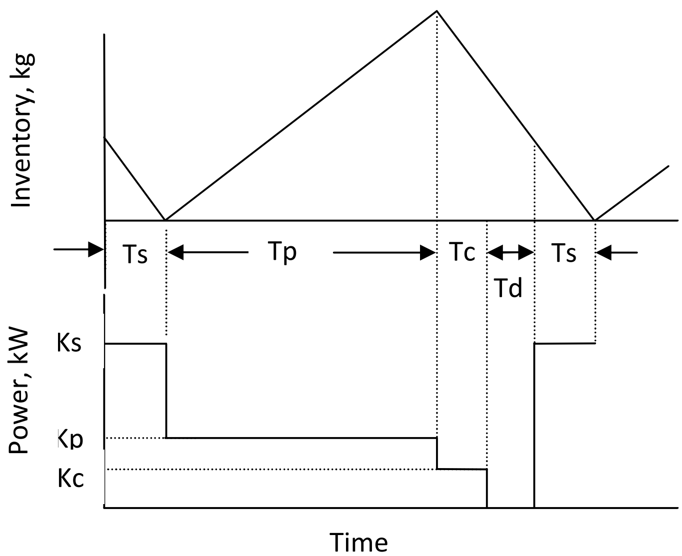

Fig. 1: Inventory and Power Curves for Model 1

We define the following parameters and decision variables for this model:

Parameters:

Ks	Power consumed during start-up (kW)
Kp	Power consumed during production (kW)
Kc	Power consumed during chloride dissolution (kW)
Ts	Start-up time after a complete shutdown (h) = 8 h
Tc	Chloride dissolution time (h) = 21 h

D	Demand rate from the downstream machines (kg/h)
I	Rate of interest (1/h)
C	Cost of the material (Rs/kg)
UEC	Unit energy cost (Rs/kWh) = 2 Rs/kWh

Decision Variables

Tp	Production time (h)
Td	Shutdown time (h)

The objective function and the constraints are defined next.

Objective Function

Minimize (Energy Cost + Inventory Holding Cost) per unit time

i.e.,

Minimize [1/(Ts + Tp + Tc + Td)]

[{(Ks)(Ts) + (Kp)(Tp) + (Kc)(Tc)}(UEC)

+ {(1/2)(D)(Ts + Tc +Td)(Ts + Tp + Tc + Td)(I)(C)}]

Constraints

1. (D))(Ts + Tp + Tc + Td)/Tp <= Maximum rate of production during that plan period
2. (Ts + Tp + Tc) <= 168 (= seven days)
3. Tp, Td >= 0

During the start-up period the energy requirement is the maximum. The unit energy cost (UEC) is taken as Rs. 2.00 per kWh.

Estimation of Parameters for Model 1

For a start-up after shutdown, total load connected is taken. Hence,

$Ks = 360$ kW

It takes 8 hours to reach its operating temperature. Hence,

$Ts = 8$ h.

During production, it has been observed that power consumed is 135 kW. Hence,

$Kp = 135$ kW.

From the process of chloride dissolution the value Kc can be calculated as follows. On a chloride dissolution day with shutdown on the following day,

$(Kc)(Tc) = 748.32$ kWh.

But $Tc = 21$ h.

Hence,

$Kc = 35.63$ kW.

Inventory carrying cost (ICC) is calculated as under:

ICC = (Inventory quantity, kg)(Interest rate, 1/h)(Cost of component, Rs/kg)

Cost of component, Rs/kg = Cost of material, Rs/kg + Value added, Rs/kg

Value added, Rs/kg = (Total Cost, Rs – Cost of Energy, Rs) / Weight of material, kg

The model was solved using the GAMS software package. The actual figures for the demand for the final product in the months of April through September were taken and were used to calculate the demand in terms of kg per hour (kg/h). The results are given in Table 3.

Table 3: Optimal Shutdown Results Using Model 1

Month	Demand (kg/h)	Tp (h)	Td (h)	Inventory Carrying Cost (Rs/h/)	Energy Cost (Rs/h/)	Total Cost (Rs/h/)
Apr	102.8	139	115.8	14.51	157.79	172.30
May	105.0	139	109.8	14.21	161.19	175.40
Jun	128.9	139	55.4	10.98	197.82	208.79
Jul	157.3	139	17.6	7.14	241.32	248.45
Aug	146.9	139	30.6	8.53	225.48	234.01
Sep	128.7	139	58.7	11.00	197.54	208.54

Model 2

Model 2 assumes that the heat-treatment cycle consists of a number of sub-cycles, each containing the start-up, the production, and the chloride dissolution phases, with the last sub-cycle followed by a shutdown. It is assumed that the production time does not exceed 6 days. Here the decision variables are the production time, the shutdown time, the production rate of the furnace, and the number of sub-cycles in a plan period. Figure 2 shows the inventory and the power consumption curves for such a model assuming that the number of sub-cycles, n, is 3.

The parameters, the decision variables, the objective function, and the constraints for these models are given below:

Parameters

Ks1	Power consumed during start-up after a shutdown (kW)
Ks2	Power consumed during start-up after chloride dissolution (kW)
Kp	Power consumed during production (kW)
Kc	Power consumed during chloride dissolution (kW)
Kcn	Power consumed during the last chloride dissolution (kW)
Ts1	Time to start up after shutdown (h)
Ts2	Time to start up after chloride dissolution (h)
Tc	Chloride dissolution time (h)
Tcn	Chloride dissolution time after n sub-cycles (h)
D	Demand rate from the downstream machines (kg/h)
I	Rate of interest (1/h)
C	Cost of the material (Rs/kg)

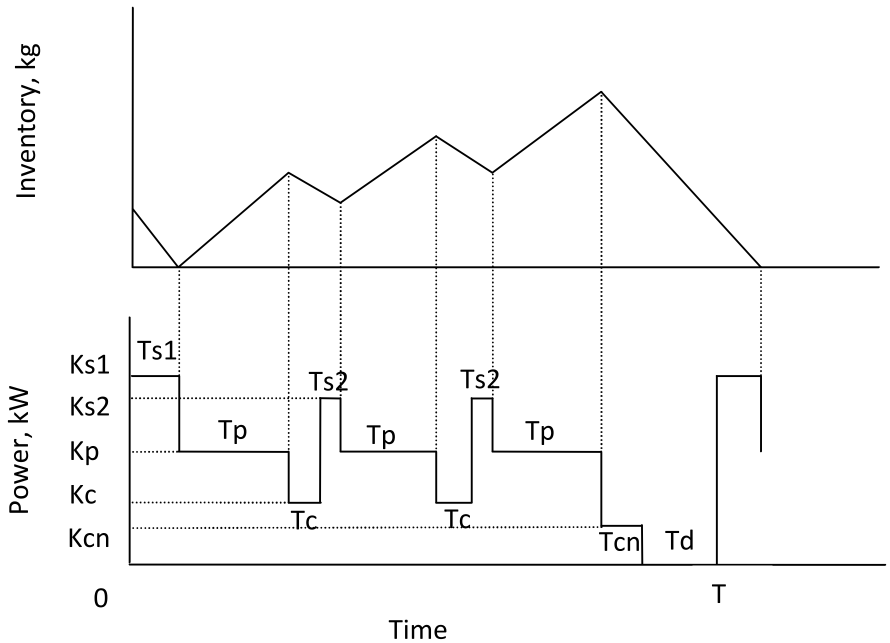

Fig. 2: Inventory and Power Consumption Curves for Model 2

Decision Variables

Tp	Production time (h)
Td	Shutdown time (h)
P	Production rate of the furnace (kg/h)
n	Number of sub-cycles in a plan period

It may be noted that the total duration of one start-up, one production period, and one chloride dissolution is called a sub-cycle.

Objective Function

Minimize (Energy cost + Inventory Holding Cost) per unit time

Minimize [1/(Ts1 + (n-1)(Ts2 + Tc) + (n)(Tp) + Tcn + Td)]

[{(Ks1)(Ts1) +(Kcn)(Tcn) + (Kp)(Tp) + (n-1){(Ks2)(Ts2) + (Kc)(Tc) + (Kp)(Tp)}}(UEC)

+ (1/2){(D)(Tc + Ts1 – Ts2 +Td)(Tc) +Ts1 – Ts2 + Td}

+ (n){(p-D)(Tp)(Tp + (2) (Tc + Ts2)) – (D)(Tc + Ts2)(Tc + Ts2)}

+ {(p-D)(Tp) – (D)(Tc + Ts2)(Tp + Tc + Ts2)(n)(n-1))}(I)(c)]

Constraints:

1. P <= Maxiumum rate of production during that plan period
2. Ts1 +Tp + Tc < = 168 (= hours in seven days)
3. (n)(p – D)(Tp) – (n -1)(D)(Tc + Ts2) – (D)(Tcn + Ts1 + Td) =0

   i.e., Total production = Total demand

4. Ts1 + (n – 1) (Ts2 + Tc) + (n)(Tp) + Tcn + Td <= Length of the plan period
5. (P – D)(Tp) >= (D)(Tc + Ts2)

   i.e., inventory should be non-negative after every sub-cycle

   Tp, Td, n, and P >= 0

Estimation of Parameters for Model 2

As before,

$Ks1 = 360$ kW.

From the chloride dissolution process the value of $(Ks2)(Ts2) = 174$ kWh. ButTs2 = 45 min = 0.75 h. Hence

$Ks2 = 242$ kW.

Kc is the same as the power consumed on a chloride dissolution day.

$(Kc)(Tc) = 2{,}412$ kWh

The chloride dissolution time (Tc) is 24 hours. Hence, Kp can be taken as equal to 100 kW:

$Kc = 100$ kW

The power required at the end of the cycle for the chloride dissolution (Kcn) is the same as in Model 1. That is,

$Kcn = 35.63$ kW

The power consumption during the production period is given as the same as that in Model 1:

$Kp = 135$ kW

Using the demand in terms of weight of material per hour (kg/h) and using the GAMS software package, the optimal shutdown results were obtained. They are given in Table 4.

Table 4: Optimal Shutdown Results Using Model 2

Month	Demand (D) (kg/h)	Number of cycles (*n*)	Tp (h)	Td (h)	Inventory Carrying Cost (Rs/h/)	Energy Cost (Rs/h/)	Total Cost (Rs/h/)
Apr	102.8	1.0	136	112.7	16.79	158.35	175.13
May	105.0	2.6	136	289.9	21.47	157.00	178.47
Jun	128.9	3.2	136	193.2	12.38	192.01	204.39
Jul	157.3	1.0	136	16.6	8.59	242.18	250.76
Aug	146.9	3.7	136	120.1	4.16	218.46	222.65
Sep	128.7	3.2	136	194.0	12.45	191.75	204.20

Model 3

This model considers the case when the furnace can be maintained at a low temperature immediately after the production phase but before it starts again. It may have the benefit of a reduced inventory level and a reduced energy cost. Here the decision variables are the production time before the low temperature period, the production time after the low temperature period, the time duration of the low temperature period, the shutdown time, the production rate of the furnace, and the number of sub-cycles in a plan period.

Ks1 Power consumed during start-up after a shutdown (kW)

Ks2 Power consumed during start-up after chloride dissolution (kW)

Ksn	Power consumed during start-up after maintaining the furnace at a lower temperature than the operating temperature (kW)
Kp	Power consumed during production (kW)
Kpn	Power consumed during the period in which the furnace is maintained at a lower temperature than the operating temperature (kW)
Kc	Power consumed during chloride dissolution (kW)
Kcn	Power consumed during the last (nth) chloride dissolution (kW)
Ts1	Start-up time after complete shutdown (h)
Ts2	Start-up time after chloride dissolution (h)
Tsn	Start-up time after maintaining the furnace at a lower temperature (h)
Tc	Chloride dissolution time (h)
Tcn	Chloride dissolution time after n sub-cycles (h)
D	Demand rate from the downstream machines (kg/h)
I	Rate of interest (1/h)
C	Cost of the material (Rs/kg)

Decision Variables

Tp1	Production time before the furnace is maintained at a lower temperature (h)
Tp2	Production time after the furnace is maintained at a lower temperature (h)

Tpn Time duration for which the furnace is maintained at a lower temperature than the operating temperature (h)

Td Shutdown time (h)

P Production rate of the furnace (kg/h)

n Number of sub-cycles in a plan period

It may be noted that the total duration of one start-up, two production periods separated by a period of low temperature, and one chloride dissolution is called a sub-cycle.

Figure 3 shows the inventory and the power consumption curves when the furnace is operated following the assumptions underlying Model 3.

Objective Function

Minimize (Energy Cost + Inventory Holding Costing) per unit time

where,

Energy Cost per Time

$$= (1/T)\ [(Ks1)(Ts1) + (Ks1)(Ts1) + (Kcn)(Tcn) + (Kp)(Tp1 + Tp2)$$

$$+ (n)\{(Kpn)(Tpn) + (Ksn)(Tsn)\} + (n-1)\{(Ks2)(Ts2) + (Kc)(Tc)\}$$

$$+ (Kp)(Tp1 + Tp2)](UEC)$$

Inventory Holding Cost per Time = (1/T) [(1/2)(n)(A1 + A2 + A3) + (n)(n-1)(A4) + A5) (I)(C)]

$$T = Ts1 + (n-1)(Ts2 + Tc) + (n)(Tp1 + Tp2 + Tpn + Tsn) + Tcn + Td$$

$$A1 = (1/2)[(P-D)(Tp1)\ (Tp1 + (2)(Tpn) + (2)(Tsn)) – (D)(Tpn + Tsn)(Tpn + Tsn)]$$

$$A2 = (1/2)[(P-D)(2)(Tp1 + Tp2) – (2)\ (D)(Tpn + Tsn)]\ (Tp2)$$

$$A3 = (1/2)[(2)(P-D)(Tp1 + Tp2) – (D)\ \{(2)\ (Tpn + Tsn) +Tc + Ts2\}](Tc + Ts2)$$

$$A4 = [(P-D)(Tp1 + Tp2) – (D)(Tpn + Tsn +Tc + Ts2)(Tc + Ts2)]$$

$$(Tp1 + Tpn + Tp2 + Tsn + Tc + Ts2)$$

$$A5 = (1/2)(D)(Td + Ts1 – Ts2)(Td + Ts1 – Ts2)$$

Constraints:

1. P <= Maxiumum rate of production during that plan period
2. Ts1 + (n-1)(Ts2 + Tc) + (n)(Tp1 + Tp2 – Tpn +Tsn) + Tcn + Td = 720
3. (n){(p – D)(Tp)(Tp1 + Tp2) – (D)(Tsn + Tpn + Tc + Ts2)} – (D)(Td + Ts1 – Ts2) =0
4. (P – D)(Tp1 + Tp2)>=(D)(Tsn + Tpn + Tc + Ts2)
5. (P – D)(Tp1)>=(D)(Tpn)

Tp1, Tp2, Tpn, Td,n, and P >= 0

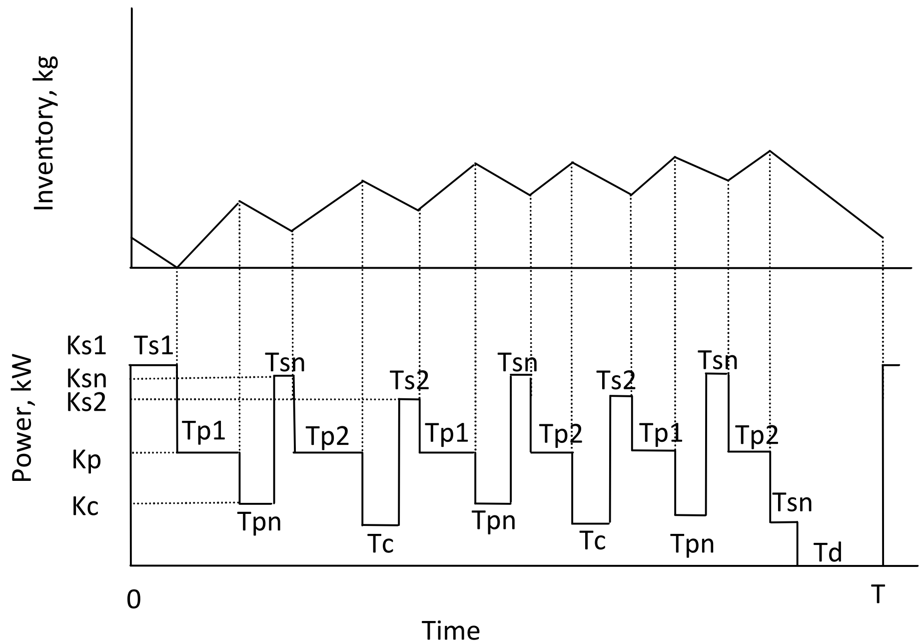

Fig. 3: Inventory and Power Consumption Curves for Model 3

Estimation of Parameters for Model 3

The power consumed Ks1, Ks2, Kc,Kcn, and Kp are the same as those compute for the Model 2.

The power required for the maintenance of the furnace at low temperature Kpn, is measured as

Kpn = 110 kW.

The power required to bring back the furnace to the operating temperatures from maintenance at low temperature condition, Ksn, is measured as

Ksn = 260 kW

Table 5 gives the optimal shutdown results for Model 3 as obtained by using the GAMS software package.

Table 5: Optimal Shutdown Results Using Model 3

Month	D (kg/h)	*n*	Tp1 (h)	Tp2 (h)	Tpn (h)	Td (h)	ICC (Rs/h)	EC (Rs/h)	TC (Rs/h)
April	102.8	1.0	134.0	0.0	1.25	108.8	7.32	162.7	170.00
May	105.0	1.0	1.2	132.8	1.25	105.5	7.18	166.0	173.20
June	128.9	1.4	45.0	88.9	1.25	73.7	7.75	201.3	209.00
July	157.3	2.4	3.7	130.3	1.25	37.2	7.01	241.3	248.30
Aug	146.9	3.9	17.0	111.3	1.25	80.1	11.80	232.0	243.80
Sept	128.7	1.4	46.7	87.3	1.25	73.9	7.75	201.0	208.80

Table 6 gives the minimum total cost shutdown schedule and the minimum energy cost optimal schedule for every month as obtained for the various models.

Table 6: Comparing Optimal Shutdown Results for All the Models

Month	Demand	Minimum Total Cost (Rs/h)		Energy Cost (Rs/h)	
		Value	Model	Value	Model
Apr	102.8	173.00	3	157.8	1
May	105.1	173.20	3	157.0	2
Jun	128.9	204.39	2	192.0	2
Jul	157.3	248.30	3	241.3	3
Aug	146.5	222.65	2	218.4	2
Sep	128.8	204.20	2	191.7	2

Discussion

The results given in Table 5 and Table 6 show the following:

1. The practice of shutting down the furnace after every chloride dissolution operation is not the best strategy. It is more cost effective to have a number of heat-treatment sub-cycles before shutting down the furnace.
2. In all the cases the energy cost is much larger compared to the inventory carrying cost. Thus if the management decides to ignore the inventory carrying cost and takes the shutdown decision on the basis of only the energy cost, then the decisions do not

vary much except when the demand is very less. When the demand is very less, then it is found that shutting down the furnace after every heat-treatment cycle (Model 1) is better.

The strategy of shutting down the furnace during the slack time helps in many ways:

1. The power consumption and hence the power cost are substantially reduced during the shutdown period.
2. The evaporation losses due to maintenance without material can be saved.
3. Because the demand for material is known in advance, it is possible to hold the needed inventory so that the inventory holding cost is the minimum.
4. An ancillary advantage of implementing the strategy of shutting down the furnace is that the manpower deployed in the furnace may be used for other purposes in other departments, thereby saving on company overtime.