INTEGRATED PRODUCTION AND MAINTENANCE PLANNING
Modeling Corrective Maintenance

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Abstract: We are given a production system composed of several parallel machines subject to random failures. A set of items are to be produced in lots on these machines. To prevent failure production system must be maintained. We assume that these maintenance actions have an effect on the available production capacity of each machine. The objective is to generate an integrated production and preventive maintenance plan that optimizes the total costs for the system. In this paper we first discuss an existing mathematical formulation of the problem and then propose an extension and illustrate it with an example.

1 INTRODUCTION

The recent past years have witnessed a very strong increase in competition between manufacturing companies worldwide. To cope with a tough competition from immerging low-wage countries and to insure their market position, most of the western companies invested in highly automated quality machinery. These machines typically require fewer operators, produce high quality products, but are also more expensive. Therefore, a company with such modern machinery has to optimize the utilization of the production capacity in order be profitable (Aghezzaf et al., 2008).

In such a system the production capacity depends on two processes: the production process itself and the maintenance process. In most companies, these two processes are planned independently. The result is that conflicts may arise between both plans. It is clear that both processes have a large influence on each other. Therefore, it is useful to develop a planning model that integrates both production and maintenance.

2 STATE OF THE ART

As the importance of integrating production and maintenance started growing over the recent past few years, some studies have tried to study the integrated problem. Ashayeri et al. (1996) investigated this problem by performing a case study in the process industry. They worked out an integrated model for a multi-machine production system but at the operational level. A large disadvantage was the use of discrete chances to simulate machine failure instead of the normally used failure rate function. Graves & Lee (1999) investigated an integrated planning for a single machine also at an operational level. They used the total weighted completion time as criteria for the solution. The drawback here is the fact that only one maintenance activity was allowed during the time horizon. Later, Lee & Chen (2000) extended this model to several parallel machines and then to job shops.

While the above studies focus on the operational level, Wienstein & Chung (1999) have proposed a mixed integer program to evaluate the maintenance policy of a company at the aggregate planning level. They minimize the sum of the production costs, the labor costs and the maintenance costs. Another integrated model at the aggregate level, developed by Cassady and Kutanoglu (2005), minimizes the weighted completion time of the jobs. Both aforementioned aggregate planning models take into account preventive maintenance actions, but they ignore reactive maintenance. Aghezzaf et al. (2007) satisfy this lack by presenting a model that explicitly takes into consideration the reliability parameters of the system. The objective of this

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single machine model is the minimization of fixed and variable production costs, inventory costs, and costs related to preventive and corrective maintenance activities. An extension to parallel machines is given by Aghezzaf and Najid (2008). Berrichi et al. (2009) also consider the parallel machine problem. They propose two genetic algorithms to solve a bi-objective model for joint production and maintenance scheduling. The first objective is related to production scheduling and is the minimization of the makespan. The second objective is related to maintenance scheduling and is the minimization of the system unavailability. Berrichi et al. (2010) present an ant colony based heuristic to solve the latter problem leading to superior results.

3 MODEL AND SOLUTION ALGORITHM

In this section we propose some alterations for the mathematical formulation proposed by Aghezzaf and Najid (2008). We will recapitulate this formulation and extend the solution algorithm as proposed by Aghezzaf et al. (2007) for a single machine system. We will immediately refer to the rewritten model which can be solved in CPLEX, for the original model formulation we refer to Aghezzaf and Najid (2008).

The goal of the model is to generate a production planning so that each product $i \in P$ fulfills the demand d_{it}. Each machine has a limited capacity κ_m that is consumed by the production process, but also by the maintenance activities. In order to simulate machine failure, a failure rate distribution is used. Assume that preventive maintenance will restore the machine to 'as-good-as-new'. Reactive maintenance will return the machine to an 'as-good-as-old' status. This means only minimal repair is performed at failure. The PM policy has to be determined by the preventive maintenance cycle $= k_m\tau$. The model will, besides the production planning, also return the optimal values of k_m.

Sets and Parameters

H	Set of all the periods in the planning horizon
P	Set of all the products
M	Set of all the machines, $m = 1, \dots, M$
c_m^p	Cost of each preventive maintenance on machine *m*
c_m^r	Cost to carry out a corrective maintenance action on machine *m* $\left(c_m^p \leq c_m^r\right)$
d_{it}	Demand for item *i* in period *t*
f_{it}^m	Fixed cost of producing item *i* in period *t* on machine *m*
h_{it}	Variable holding cost of item *i* in period *t*
κ_m	Nominal capacity (given in time units) of machine m
p_{it}^m	Variable cost of producing item *i* in period *t* on machine *m*
ρ_{im}	Process time for each unit *i* on machine *m*
$r_m(t)$	Failure rate distribution for machine *m*
τ	The basic planning period duration
N	Number of periods of fixed length τ within the planning horizon
k_m	Number of periods of fixed length τ within the preventive maintenance cycle of machine *m*
n_{I_m}	Number of preventive maintenance activities for machine *m* during the time horizon $\left(n_{I_m} = \lfloor N/k_m \rfloor\right)$
L_m^p	Capacity usage because of preventive maintenance on machine *m*
L_m^r	Capacity usage because of reactive maintenance on machine *m*

Variables

x_{it}^m	Quantity of item *i* produced in period t on machine m
I_{it}	Inventory of item *i* at the end of period *t*
y_{it}^m	Binary variable $\begin{cases} =1 & \text{if item } i \text{ is produced in period } t \text{ on machine } m \\ =0 & \text{otherwise} \end{cases}$
$\kappa_m(t)$	Available capacity (given in time units) of machine m in period t

Mathematical Model

$$\text{Minimize } Z(k_1, k_2, \dots, k_M) = \sum_{m\in M}\sum_{n=1}^{n_{I_m}}\left(c_m^p + \sum_{t=(n-1)k_m+1, t\leq N}^{nk_m}\left(c_m^r\int_0^\tau r_m(u + (t-(n-1)k_m-1)\tau)du + \sum_{i\in P}(f_{it}^m y_{it}^m + p_{it}^m x_{it}^m)\right)\right) + \sum_{t\in H}\sum_{i\in P} h_{it}I_{it} \quad (1)$$

Subject to,

$$\sum_{m\in M} x_{it}^m + I_{i,t-1} - I_{it} = d_{it} \quad \forall t \in H, i \in P \quad (2)$$

$$x_{it}^m \leq \left(\sum_{s\in H, s\geq t} d_{is}\right) y_{it}^m \quad \forall m \in M, t \in H, i \in P \quad (3)$$

$$\sum_{i \in P} \rho_{im} x_{it}^m \leq \kappa_m(t)$$

with, $\kappa_m(t)$

$$\begin{cases} = \kappa_m - L_m^p - L_m^r \int_0^\tau r_m(u + (t-1)\tau)du \\ \quad \text{if } t = (n-1)k_m + 1 \text{, i.e. if preventive maintenance is done in period } t \text{ on machine } m \\ = \kappa_m - L_m^r \int_0^\tau r_m(u + (t-1)\tau)du \\ \quad \text{if } (n-1)k_m + 2 \leq t \leq nk_m \end{cases} \tag{4}$$

$\forall m \in M, 1 \leq n \leq n_{I_m}$

$\forall (n-1)k_m \leq t \leq nk_m, t \leq N$

$$x_{it}^m, I_{it} \geq 0;\ k_m \in N;\ y_{it}^m \in \{0,1\} \tag{5}$$

$\forall i \in P, m \in M, t \in H$

We argue that the model as presented above does not accurately calculate the reactive maintenance costs. In periods in which no production is planned on one or both machines, reactive maintenance is still counted. To avoid this cost miscalculation, we introduce a new binary variable z_t^m. The objective function can now be changed as in (1') whereby reactive maintenance on a machine m will only be incurred if production is planned in that certain period t. By adding a new constraint (6) we ensure that all variables z_t^m are assigned the correct values.

z_t^m Binary variable
$$\begin{cases} =1 & \text{if there is production in period } t \text{ on machine } m \\ =0 & \text{otherwise} \end{cases}$$

Minimize $Z(k_1, k_2, \ldots, k_M) =$

$$\sum_{m \in M} \sum_{n=1}^{n_{I_m}} \left(c_m^p + \sum_{t=(n-1)k_m+1, t \leq N}^{nk_m} \left(c_m^r \boldsymbol{z_t^m} \int_0^\tau r_m(u + (t-(n-1)k_m - 1)\tau)du + \sum_{i \in P} (f_{it}^m y_{it}^m + p_{it}^m x_{it}^m) \right) \right) + \sum_{t \in H} \sum_{i \in P} h_{it} I_{it} \tag{1'}$$

$$z_t^m \geq y_{it}^m \tag{6}$$

$\forall i \in P, m \in M, t \in H$

The model can now be solved by the solution algorithm proposed in Aghezzaf et al. (2007), extended for parallel machines.

4 COMPUTATIONAL RESULTS

The model for parallel machines proposed in this paper is now compared with the original model introduced by Aghezzaf and Najid (2008). It is investigated if the new model generates significantly different solutions and the impact on total costs is evaluated.

Assume the time horizon consists of 8τ periods. The production system of a company consists of two machines, a new one (M1) and an old one (M2). Due to the age difference, some of the parameters for the two machines are different. These parameters are summarized in Table 1. The inventory costs (h_{it}) are independent of the product and the time period and are equal to 2. Finally the failure function is the same for both machines. It is a Weibull distribution with a shape and scale parameter both equal to 1.5. The values for the failure function are given in Table 2. Demand for both products is given in Table 3.

Table 1: Machine dependent parameters.

Machine 1	Machine 2
$\kappa_1 = 20$	$\kappa_2 = 15$
$c_1^p = 40$	$c_2^p = 45$
$c_1^r = 35$	$c_2^r = 40$
$L_1^p = L_2^p = 1$	
$L_1^r = 5$	$L_2^r = 6$
$f_{it}^1 = f_{it}^2 = 25;\ \forall i \in P, t \in H$	
$p_{it}^1 = p_{it}^2 = 5;\ \forall i \in P, t \in H$	

Table 2: Failure function.

Age machine	Expected # of failures
t=1: [0, 1τ[	0.544
t=2: [1τ, 2τ[	0.995
t=3: [2τ, 3τ [	1.289
t=4: [3τ, 4τ [	1.526
t=5: [4τ, 5τ [	1.731
t=6: [5τ, 6τ [	1.914
t=7: [6τ, 7τ [	2.081
t=8: [7τ, 8τ [	2.236

Table 3: Product demand.

t	d_{1t}	d_{2t}
1	13	6
2	8	3
3	10	11
4	4	6
5	7	9
6	12	7
7	5	9
8	8	6

Results for this problem instance are shown in Table 4. When comparing results for the old and new model, optimal costs of the different maintenance policies differ relatively between 8 and 30%. These cost differences are significant and we therefore conclude that it is worthwhile using our extended model to obtain realistic cost results. In this example the optimal solution is for both models the same, i.e. $k_1 = k_2 = 5$, but the costs differ with 17%. In other cases the new model might even lead to a different optimal maintenance policy.

Table 4: Cost matrix: Comparison old model with new model.

Limère et al. (2012)		Maintenance policy Machine 1							
		k=1	k=2	k=3	k=4	k=5	k=6	k=7	k=8
Maintenance policy Machine 2	k=1	1799,1	1691,8	1388,8	1693,6	1222,3	1415,1	1584,1	1758,2
	k=2	1619,1	1519,2	1225,7	1544,3	1060,4	1285,4	1450,5	1664,0
	k=3	1357,0	1258,4	1135,7	1245,8	989,7	1216,3	1286,3	1358,3
	k=4	1529,1	1438,2	1135,7	1497,3	1003,7	1203,3	1437,8	1703,1
	k=5	1253,0	1126,6	975,6	1163,0	**956,7**	1073,5	1154,5	1291,4
	k=6	1312,0	1213,4	1090,7	1252,8	993,5	1255,5	1330,1	1403,4
	k=7	1379,0	1272,4	1090,7	1344,9	993,5	1255,5	1506,9	1620,0
	k=8	1484,1	1393,2	1090,7	1495,3	953,5	1255,5	1506,9	1820,2
Aghezzaf and Najid (2008)		Maintenance policy Machine 1							
		k=1	k=2	k=3	k=4	k=5	k=6	k=7	k=8
Maintenance policy Machine 2	k=1	1951,4	1857,5	1553,0	1885,9	1408,1	1607,1	1799,9	1998,1
	k=2	1843,6	1749,7	1445,2	1778,0	1300,2	1499,2	1692,0	1890,3
	k=3	1588,6	1493,7	1336,2	1512,0	1189,2	1397,2	1500,0	1623,3
	k=4	1855,6	1764,8	1462,3	1798,1	1315,3	1519,3	1712,1	1915,4
	k=5	1512,7	1417,9	1228,4	1438,2	**1149,4**	1281,4	1397,2	1535,5
	k=6	1637,3	1542,4	1388,9	1562,7	1239,9	1472,9	1585,8	1699,0
	k=7	1779,5	1688,7	1472,2	1718,0	1323,2	1556,2	1775,0	1893,3
	k=8	1955,0	1864,1	1561,6	1910,4	1414,6	1645,6	1864,4	2120,7

5 CONCLUSIONS

We made a change to the model of Aghezzaf and Najid (2008) and have shown that our model more accurately represents the real situation. In the future, the model can be further extended. For instance, a production system with machines in series can be investigated. Moreover, integration of this model at the aggregate planning level with operational scheduling models offers a new research direction.

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