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An integrated hierarchical production and maintenance-planning model

Carles Sitompul and El-Houssaine Aghezzaf
Department of Industrial Management, Ghent University, Ghent, Belgium

Abstract

Purpose – The purpose of this study is to propose and formulate an integrated hierarchical production, and maintenance-planning model.

Design/methodology/approach – The proposed model is formulated mathematically and tested for some hypothetical cases. A two-level planning is proposed to address the hierarchical planning problem, i.e. aggregate planning and detailed planning. A preventive maintenance planning is integrated into the aggregate planning, while machine breakdowns, which require corrective maintenance actions, are investigated in the detailed planning. The proposed general preventive maintenance model is tested against cyclical preventive maintenance models for some cases, and for evaluating the performance of the models, in terms of costs, and service levels.

Findings – The proposed general preventive maintenance model gives a better solution in terms of cost than the cyclical maintenance model (i.e. 6 per cent less costly), if the maintenance planning is executed separately from the production planning. In terms of service level, however, both models perform equally well with average service levels equal to 97.6 per cent. The effect of tight capacity, long maintenance duration, and small machine parameters similarly tightens the capacity. In these cases, it is shown that a stable level of capacity is more beneficial to achieve a better service level, which is gained if the preventive maintenance actions are carried out monthly.

Practical implications – At the aggregate level, the proposed preventive maintenance model considers a non-cyclical planning, which means that the preventive maintenance periods do not necessarily fall at equally distant times. The inventory movement constraints at the aggregate level decouple machines to operate independently; hence the detailed level problem can be solved separately for each machine. In a rolling horizon approach, only the first period of the aggregate plan is implemented and disaggregated into the production of items at the detailed level.

Originality/value – The paper proposes an integrated model of hierarchical production and maintenance planning. A general preventive maintenance is integrated into the aggregate planning, while machine breakdowns are investigated in the detailed planning. To the best of one's knowledge, such a hierarchical view of production planning and maintenance has not been addressed adequately.

Keywords Production, Preventive maintenance, Hierarchical control

Paper type Research paper

Introduction

In a failure prone manufacturing system, a maladjusted maintenance planning policy can be a source of significant unnecessary extra expenses resulting from production re-planning, unpredictable product quality and in-service levels. It is therefore essential to carry out both production planning and maintenance in an integrated and effective way to improve the performance of the whole system.

Studies investigating the issue of integrating production and maintenance have shown some very promising results. However, most of these studies are dedicated to the integration of maintenance and production planning at the operational level and

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only few tackled the problem at an aggregate level. Li and Cao (1995) and Li and Glazebrook (1998), among others, studied the stochastic scheduling problem subject to machine breakdowns. They assume that both processing time and due dates are stochastic and machines are subject to lengthy and unpredictable breakdowns. The complexity of incomplete information about the availability of machines is analyzed considering the completion times and due dates criteria. They evaluate some polynomial and approximation algorithms for most cases and enumerative algorithms for some cases. Albers and Schmidt (2001) show an optimal algorithm if the next point in time where the set of available machine changes is known. Otherwise, a near optimal algorithm is proposed. They show that not knowing machine availabilities in advance is not harmful to the quality of the solution. Alcaide *et al.* (2002) propose a procedure, which converts scheduling problem with machine breakdowns into a finite sequence of problems without breakdowns, i.e. they measure the length of availability periods and repair times. Kubiak *et al.* (2002) and Allaoui and Artiba (2006) propose branch and bound algorithms in a flow shop environment with machine availability. An extensive review of the scheduling problem subject to machine breakdowns is available in Schmidt (2000).

Groenevelt *et al.* (1992a) study the production lot-sizing problem subject to machine breakdowns. They evaluate the effect of no-resumption policy and abort/resume policy on economic lot sizing decisions. Lin and Kroll (2006) study the economic lot-sizing problem assuming that the production run is aborted when a breakdown occurs (no-resumption policy). The production run is resumed only after all on-hand inventories are depleted. The approximation procedure is proposed and tested on some numerical examples with both linear deterioration and exponential deterioration models. Recently, Chakraborty *et al.* (2008) study the lot-sizing problem when production systems deteriorate and may ultimately breakdown afterwards. A preventive maintenance is performed at the end of a production run and corrective maintenance is executed when a machine breakdown occurs during the production run. They assume perfect repair and derive the criteria for the existence and uniqueness of an optimal lot size under general breakdown and general repair distributions.

Buffering techniques to deal with the uncertain capacity due to machine breakdowns has been widely employed by authors such as Groenevelt *et al.* (1992b), Crespo Marguez *et al.* (2003) and Chelby *et al.* (2008). Groenevelt *et al.* (1992b) use safety stocks on the economic lot-sizing problem to meet a prescribed service level. The safety stock is depleted whenever the machine is broken and has undergone repair. They propose a production control policy and derive an optimal lot-sizing model under this policy. Chelby *et al.* (2008) simultaneously determine the preventive maintenance period (i.e. maintenance cycle size) and the size of safety stocks, which minimize the total average cost per time unit. Crespo Marguez *et al.* (2003) use buffer capacity to cope with unexpected breakdowns and to deal with the variability of demand and production lead times. They simulate and evaluate some maintenance policies, such as age-based maintenance policy and buffer-based policy, using systems dynamics models.

A recent development in the integration of maintenance and production planning is the consideration of product quality in the planning model, e.g. Ben-Daya (1999), Panagiotidou and Tagaras (2008) and Radhoui *et al.* (2009). In addition to deteriorating with age, a machine may experience a quality shift (i.e. jump to an out-of-control state).

In this case, Ben-Daya (1999) develops an integrated model optimizing the economic lot sizing problem, economic design of – $\bar{x}$-control chart and preventive maintenance model. Panagiotidou and Tagaras (2008) propose a combination of an age-based preventive maintenance, which restores the machine into an "as-good-as-new" status, and some additional minimal repairs, which upgrades the machine from an out-of-control to the in-control state. Radhoui *et al.* (2009) develop an integrated model determining the optimal threshold for the proportion of non-conforming units in a lot and the optimal buffer size, which minimize the average costs of maintenance, quality, and inventory.

Only few papers address the integration of maintenance and aggregate production planning, such as Weinstein and Chung (1999), Aghezzaf *et al.* (2007), Aghezzaf and Najid (2008) and Aghezzaf *et al.* (2008). Weinstein and Chung (1999) study the integration of maintenance and hierarchical production planning and propose a three-phase approach. The first phase executes the aggregate production planning which includes the aggregate requirements for proactive maintenance activities specified by a maintenance policy. In the second phase, a master production schedule is generated using a multiple goal linear programming model. The objective is to minimize the sum of backordering cost and the weighted deviations from goals for production, inventory, and overtime obtained from the previous phase. The third phase simulates the master production schedule and maintenance plan to evaluate the consequences of the maintenance policy on completion of the master production schedule. This approach is driven by maintenance policies set by the decision maker before the three-stage approach is executed. Run-based maintenance policy and interval based maintenance policy are evaluated using some experimental parameters. Aghezzaf *et al.* (2007) propose a basic model for single machine production systems. Unlike Weinstein and Chung (1999), they model both maintenance planning and production planning simultaneously. They propose a solution approach, which is based on a cyclical policy, i.e. the cycle size of maintenance period is fixed. An illustrative example shows that solving production planning and maintenance planning independently may be feasible but not optimal. In Aghezzaf and Najid(2008) and Aghezzaf *et al.* (2008), the model is extended to production systems with several production lines. A general preventive maintenance policy is proposed and used as a lower bound to test a Lagrangian heuristic. The general policy relaxes the cyclical restriction and establishes – for each production line – specific maintenance periods, which do not necessarily fall at equally distant epochs. The solution gap analysis shows that capacity tightness has a great impact on the quality of the Lagrangian heuristic. When capacity is loose, the heuristic produces feasible near-optimal integrated plans (i.e. gap is approximately 2 per cent).

Although most companies execute their planning hierarchically, the integrated maintenance and hierarchical production planning has not yet been addressed adequately. The first publication of hierarchical production planning can be attributed to Hax and Meal (1975), which is then, solved using Lagrangian technique by Graves (1982). Bitran *et al.* (1981) study the hierarchical production planning systems and propose a modified knapsack method when disaggregating a product family into items. They show the relation between the tactical planning and the detailed planning and the need to address the feasibility and consistency issues during disaggregation. Bitran *et al.* (1982) modify the framework for a two-stage system and show that even in case of deterministic demand, a consistent disaggregation is difficult to obtain. We conjecture that the preventive maintenance planning should be integrated in the tactical level planning and uncertainty due to machine breakdowns should be tackled in the detailed level planning.

Problem formulation

Let P be the set of product families and N_k be the set of items belonging to product family. Let H be the planning horizon consisting of W periods. Each item $j \in N_k$ has a periodic demand denoted by $d_{jk}(w), \forall w \in H$. Figure 1 shows the machine layout of the production system. The production system is a flow shop layout having M stages, where all items must go from stage 1 through stage M. Stage 1 is assumed to have a sufficient amount of raw material. We assume that each stage has one machine, $m \in \{1, 2, \ldots, M\}$, i.e. stage 1 has machine 1, and stage 2 has machine 2 and so on. Each machine follows a Weibull failure distribution with shape parameter α and scale parameter β. Let $r_m(t)$ denotes the failure rate function of machine m in period t and be given by:

$$r_m(t) = \frac{f_m(t)}{F_m(t)},$$

where $f_m(t)$ and $F_m(t)$ denote the failure probability function and the cumulative density function respectively.

We propose a two-level approach to model the integration of hierarchical production planning and maintenance planning. At the first level (i.e. aggregate level), the set of product families P is produced during W-periods of planning horizon H. At this level, machines are aggregated as a single production line that is preventively maintained. At the second level (i.e. detailed level), the planned quantity of each product family is disaggregated into items belonging to its corresponding family with the objective to save some setup costs in the future periods subject to machine breakdowns. If a machine breaks down then a corrective maintenance is needed to repair the machine back to the status before it failed.

Aggregate planning and preventive maintenance

Let H be the planning horizon of length WT covering W periods of fixed length T, e.g. $W = 12$ and $T = 1$ month, for one year planning horizon. Let the production rate of each machine in one unit T be denoted by κ_m (in hours/month). Let t_m^{pr} be the constant duration of preventive maintenance of machine m (in hours). Assume also that when a breakdown occurs, a constant duration of is needed to repair the machine. Let $t_m^{mt}(v, w)$ be the expected maintenance duration when the last preventive maintenance action took place in period $v, v \leq w$. The expected maintenance duration is then given by:

Figure 1.
Production layout

$$t_m^{mt}(v,w) = \begin{cases} t_m^{pr} + t_m^{cr}\displaystyle\int_0^T r_m(t)dt, & \text{if } v = w, \\ t_m^{cr}\displaystyle\int_0^T r_m(t+(w-w)T)dt, & \text{if } v \leq w. \end{cases}$$

We assume that preventive maintenance is executed at the level of the production line, which means that all machines are maintained during the preventive maintenance action. The corrective maintenance is executed only if a machine breaks down. Let c_m^{pr} be the preventive maintenance cost of machine m and c_m^{cr} be the corrective maintenance cost of machine m. The expected maintenance cost of machine m is given by:

$$c_m^{mt}(v,w) = \begin{cases} c_m^{pr} + c_m^{cr}\displaystyle\int_0^T r_m(t)dt, & \text{if } v = w, \\ c_m^{cr}\displaystyle\int_0^T r_m(t+(w-w)T)dt, & \text{if } v \leq w. \end{cases}$$

Let $Z_{mt}(v,w)$ be a binary variable equals to 1 if the preventive maintenance in period v covers period w, $v \leq w$ and zero otherwise. The expected capacity of machine m in period w is then given by:

$$\kappa_m(w) = \kappa_m - \sum_{v \in H, v \leq w} t_m^{mt}(v,w) Z_{mt}(v,w)$$

The following parameters for the family production planning are defined. Let $c_{km}^{p}(w)$ be the variable production cost of product family k at machine m in period w (in €/unit) and $h_{km}(w)$ be the holding cost of product family k at machine m in period w (in €/unit/period). For the sake of simplicity, we do not take into account labour related costs, such as overtime, hiring and laying off. Let denotes the hours required for machine m to produce one unit of product family k. Let $f_{km}(w)$ be the fixed setup cost if production of family k at machine m takes place in period w (in €). Let $X_{km}(w)$ be the quantity of product family k produced in period w (in units) and $Y_{km}(w)$ be the binary variable, which equals to 1 if product family k is produced at machine m in period w and zero otherwise. Let $I_{km}(w)$ be the inventory level for product family k at machine m at the end of period w (in units). The integrated family production and preventive maintenance planning is then formulated as follows:

Minimize

$$\sum_{k \in P} \sum_{m=1}^{M} \sum_{w \in H} \left(c_{km}^{p} X_{km}(w) + h_{km}(w) I_{km}(w) + f_{km}(w) Y_{km}(w) \right)$$

$$+ \sum_{m=1}^{M} \sum_{w \in H} \sum_{v \in H, v \leq w} c_m^{mt}(v,w) Z_{mt}(v,w) \tag{1}$$

subject to

$$I_{kM}(w-1) + X_{kM}(w) - D_k(w) = I_{kM}(w),\ \forall k, w, \tag{2}$$

$$I_{km}(w-1) + X_{km}(w) - X_{k,m+1}(w) = I_{km}(w),\ \forall k, w, m = 1, \ldots, M-1, \tag{3}$$

$$a_{km}X_{km}(w) \leq \kappa_m Y_{km}(w),\ \forall k, m, w, \tag{4}$$

$$\sum_{k\in P} a_{km}X_{km}(w) \leq \kappa_m - \sum_{v\in H, v\leq w} t_m^{mt}(v,w)Z_{mt}(v,w)\ \forall m, w, \tag{5}$$

$$\sum_{v\in H, v\leq w} Z_{mt}(v,w) = 1,\ \forall w, \tag{6}$$

$$X_{km}(w), I_{km}(w) \geq 0,\ \ Y_{km}(w), Z_{mt}(v,w) \in \{0,1\},$$

where $D_k(w) = \sum_{j\in N_k} d_{jk}(w)$ denotes the demand of product family k in period w.

Equation 1 shows the objective function of minimizing the total costs of production, holding, setup costs and maintenance costs. Equations 2 and 3 shows the usual inventory balance constraints at machine M (i.e. the last stage) and the other upstream stages, respectively. In equation 3, the inventory at the end of period w equals to the inventory at the end of period w-1 plus production at machine m in period w minus production at machine $m+1$ in period w (i.e. the next production machine). Equation 4 shows the fixed cost realization constraints, which means that a fixed cost is realized whenever there is a production at machine m in period w. Equation 5 shows that production is constrained by the expected capacity of machines, which depends on the maintenance decisions. Equation 6 makes sure that a preventive maintenance of the production line in a period is covered by one activity in a previous period or in that period.

Detailed planning and corrective maintenance

In a rolling horizon approach, only the first period of the aggregate plan is implemented. The production of family k at machine m in the first month $X_{km}(1)$ can be obtained from the aggregate plan. The detailed planning deals with the allocation of these quantities into items subject to machine breakdowns. The disaggregation of families into items can be formulated as follows:

$$\sum_{j\in N_k} x_{jkm}(1) = X_{km}(1),\ \forall k, m,$$

where $x_{jkm}(1)$ denotes the production of item j from family k at machine m in period 1.

To save setup costs in future periods, Bitran *et al.* (1981) propose an objective function meant to distribute the family run quantity among its items in such a way that each item's run out time coincides with the run out time of the family. Let $i_{jkm}(0)$ denote the inventory level of item j from family k at machine m at the end of period 0. If the item demand j in month 1, $d_{jk}(1)$ is known at the beginning of period 1 then the effective demand in period 1, $d^{e}_{jk}(1)$ is defined as follows:

$$d^{e}_{jk}(1) = \max\left(0, d_{jk}(1) - i_{jkM}(0)\right)$$

where $i_{jkM(0)}$ denote the inventory of item j from family k at machine M (i.e. the last machine) at the end of period 0. Let Rt_{km} be the run out time of family k in machine m and rt_{jkm} be the run out time of item j from family k, where:

$$Rt_{km} = \frac{X_{km}(1) + \sum_{j \in N_k} i_{jkm}(0)}{\sum_{j \in N_k} d^{e}_{jk}(1)}, \quad rt_{jkm} = \frac{x_{jkm}(1) + i_{jkm}(0)}{d^{e}_{jk}(1)}. \tag{7}$$

To equalize the run out time of a family and the run out time of its items, Bitran *et al.* (1981) formulate the objective function as a minimization of the sum of square differences. For purposes of simplicity, we linearize the problem and use the absolute deviation between the run out items and run out family as the objective function.

If a machine breaks down then a corrective maintenance action is needed before production can be resumed. According to Barlow and Hunter (1960), the number of failures, $S(w)$, occurring after w operating periods is considered as a Poisson process, i.e.:

$$P(S(w) = s) = \frac{R(w)^{s} e^{-R(w)}}{s!},$$

where $R(w) = \int_0^w r(u)du$. The maximum possible number of failures of machine m in period w before it loses all capacity is defined as:

$$N_m^{\max}(w) = \left| \frac{\kappa_m - t_m^{cr} Z_{mt}(w)}{t_m^{cr}} \right|,$$

where $Z_{mt}(w)$ equals to 1 if a preventive maintenance action is executed in period w, which has been decided at the aggregate level. This maximum number shows that capacity becomes zero when failures occur reaching or exceeding this number. Hence, we can sum all failures exceeding this number into one scenario of failures.

Let $\Omega_m(1) = \{0, 1, \ldots, N_m^{\max}(1)\}$ denote the set of possible scenario of failures for machine m in period 1. Let $x^{s}_{jkm}(s,1)$ denote the item production if scenario s is realized (i.e. s failures occur in period 1) and $x^{u}_{jkm}(s,1)$ denote the unmet production from the planned production if scenario s is realized. Let $rt_{jkm}(s)$ be the run out time of item j from family k at machine m if scenario s is realized. Then, the detailed planning problem can be formulated as follows:

Minimize

$$\sum_{m=1}^{M} \sum_{k \in P} \sum_{s \in \Omega_m(1)} \left(\sum_{j \in N_k} \pi(s) \left| rt_{km} - rt_{jkm}(s) \right| \right) + \omega \sum_{m=1}^{M} \sum_{k \in P} \sum_{j \in N_k} \sum_{s \in \Omega_m(1)} x^{u}_{jkm}(s,1), \tag{8}$$

subject to

$$\sum_{j \in N_k} x_{jkm}(1) = X_{km}(1), \ \forall k, m, \tag{9}$$

$$\sum_{k \in P} \sum_{j \in N_k} a_{km} x^s_{jkm}(s, 1) \leq \kappa_m - t^{pr}_m Z_{mt}(1) - t^{cr}_m s, \ \forall m, s. \tag{10}$$

$$rt_{jkm}(s) = \frac{x^s_{jkm}(s, 1) + i_{jkm}(0)}{d^e_{jk}(1)}, \ \forall k, j, m, s. \tag{11}$$

$$x^s_{jkm}(s, 1) \leq x^s_{jkm}(s - 1, 1), \ \forall k, j, m, s = 1, \ldots, N^{\max}_m, \tag{12}$$

$$x_{jkm}(1) \leq x_{jkm}(0, 1), \ \forall k, j, m, \tag{13}$$

$$x^u_{jkm}(s, 1) \geq x_{jkm}(1) - x^s_{jkm}(s, 1), \ \forall k, j, m, s, \tag{14}$$

$$x_{jkm}(1), x^s_{jkm}(s, 1), x^u_{jkm}(s, 1),$$

where $\pi(s) = P(S(1) = s)$ denotes the probability of s failures occurring in period 1 and denotes the run out time of family k as given in equation 7. Equation 8 shows the objective function, i.e. minimizing the mean absolute deviation of family's run out time and the item's run out time and the expected unmet production, which is penalized by a parameter ω. Equation 9 shows the disaggregation of family productions into items. Equation 10 shows the stochastic capacity constraint for each machine if scenario s is realized. As noted earlier, the preventive maintenance is already implemented, hence $Z_{mt}(1)$ is known. Equation 11 shows run out time of item j if scenario s is realized. Equation 12 makes sure that an item production of scenario s cannot be larger than the production of scenario $s - 1$. Equation 13 shows the item production of scenario 0 cannot be larger than the planned production. Equation 14 shows unmet production from the planned production if scenario s is realized. Note that the problem can be solved independently for each machine. The inventory movement constraints at the aggregate level decouple machines to operate independently. The disaggregation constraints make sure that the planned family production at each machine is disaggregated exhaustively to all items belonging to that family. Note also that the run out time of items is defined for each machine using the same effective demand. The model is looking for a minimum absolute deviation between run out time of items and their corresponding family, which eventually synchronizes the production of items at all machines in the production line.

Computational results

As an illustrative example, we solve a two-stage production process where each stage has one machine, which deteriorates progressively. One unit (m^2) item production in machine 2 requires one unit input from machine 1. We assume that one unit of item production requires one unit machine-hour for all machines. The hierarchy of the product can be seen in Figure 2. There are five families produced in the production line and each family has two end items. The production cost is 1 €/unit in machine 1 and 2 €/unit in machine 2. The holding cost is 0.01 €/unit/month in machine 1 and 0.03 €/unit/month in machine 2. The forecasted detailed demand for each item $d_{jk}(w)$ is given in Table I. The setup costs of family production for each machine are given in Table II, where the setup costs are high for machine 1 and low for machine 2. The machine parameters are presented in Table III. The capacity of the machine is moderately high (or medium) and the time to repair consumes 2 and 10 per cent of the machine capacity (low maintenance duration) for a preventive maintenance and corrective maintenance respectively. All parameters are given for Case 2 in Table IV, which is used as a basis for the analysis.

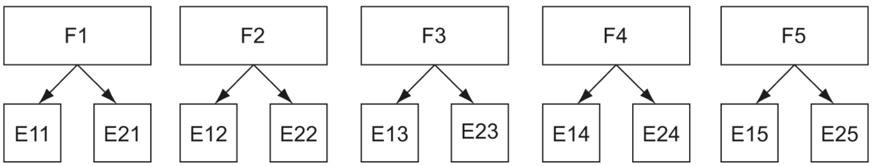

Figure 2.
A two-level product aggregation

Item	Month 1	2	3	4	5	6	7	8	9	10	11	12
E11	750	750	1500	750	750	1500	750	750	1500	750	750	1500
E21	450	450	900	450	450	900	450	450	900	450	450	900
E12	300	300	500	300	300	500	300	300	500	300	300	500
E22	350	350	400	350	350	400	350	350	400	350	350	400
E13	400	400	400	400	400	400	400	400	400	400	400	400
E23	200	200	400	200	200	400	200	200	400	200	200	400
E14	500	400	300	200	300	400	500	400	300	300	300	400
E24	250	200	150	100	150	200	250	200	150	150	150	200
E15	300	300	300	300	300	300	300	300	300	300	300	300
E25	250	250	150	150	150	150	250	250	250	150	150	150

Table I.
Forecast detailed demand (in thousand m^2)

	Machine 1	Machine 2
F1	5,500	150
F2	4,200	150
F3	5,900	150
F4	8,300	150
F5	8,700	150

Table II.
Setup costs (in €)

	κ (hours)	α	β	c_m^{pr}(€)	c_m^{cr}(€)	t_m^{pr} (hours)	t_m^{cr} (hours)
Machine 1	5,000,000	2	2	500	1,000	100,000	500,000
Machine 2	5,000,000	2	2	500	1,000	100 000	500,000

Table III.
Machine parameters

Case	Perf	General	Cyclical maintenance $nk=1$	$nk=2$	$nk=3$	$nk=4$	$nk=6$
Case 1	MC	13,500	15,000	13,500	18,000	25,500	47,500
Capacity:	HC	0	0	0	0	0	0
Loose	SC	401,400	401,400	401,400	401,400	401,400	401,400
Setup:	TC	414,900	416,400	414,900	419,400	426,900	448,900
1 High	MC2	13,530	14,830	13,690	18,070	26,370	47,640
2 Low	HC2	0	0	0	0	0	19,080
t^{pr}/t^{cr}: Low	SC2	401,400	401,400	401,400	401,400	401,400	400,718
c^{pr}/c^{cr}: Low	TC2	414,930	416,230	415,090	419,470	427,770	467,438
$\alpha, \beta = 2$	SL	100	100	100	100	100	99.43
Case 2	MC	14,000	15,000	13,500	18,000	25,500	Infeasible
Capacity:	HC	45,000	49,500	47,250	82,500	79,875	
Medium	SC	401,400	401,400	401,400	374,850	384,000	
Setup:	TC	460,400	465,900	462,150	475,350	489,375	
1 High	MC2	14,180	14,950	13,180	18,120	26,360	
2 Low	HC2	55,333	74,945	58,654	79,842	143,618	
t^{pr}/t^{cr}: Low	SC2	401,400	401,400	401,400	374,848	383,778	
c^{pr}/c^{cr}: Low	TC2	470,913	491,295	473,234	472,810	553,756	
$\alpha, \beta = 2$	SL	98.63	98.79	98.40	96.80	95.09	
Case 3	MC	14,000	15,000	13,500	18,000	Infeasible	Infeasible
Capacity	HC	113,025	120,150	115,050	175,500		
Tight	SC	371,600	369,100	383,700	331,800		
Setup	TC	498,625	504,250	512,250	525,300		
1 High	MC2	14,430	15,000	13,810	18,530		
2 Low	HC2	107,695	86,347	103,177	108,267		
t^{pr}/t^{cr}: Low	SC2	371,597	369,117	382,008	331,736		
c^{pr}/c^{cr}: Low	TC2	493,722	470,464	498 995	458,533		
$\alpha, \beta = 2$	SL	96.9	98.4	97.1	95.29		
Case 4	MC	14,000	15,000	13,500	18,000	25,500	Infeasible
Capacity	HC	45,000	49,500	47,250	82,500	79,875	
Medium	SC	18,000	18,000	18,000	17,100	17,400	
Setup	TC	77,000	82,500	78,750	117,600	122,775	
1 Low	MC2	13,980	14,980	13,760	17,930	25,130	
2 Low	HC2	21,521	28,931	37,949	83,978	105,454	
t^{pr}/t^{cr}: Low	SC2	18,000	17,998	18,000	17,094	17,392	
c^{pr}/c^{cr}: Low	TC2	53,501	61,909	69,709	119,002	147,976	
$\alpha, \beta = 2$	SL	97.4	99.15	98.43	96.7	95.64	
Case 5	MC	14,000	15,000	13,500	18,000	Infeasible	Infeasible
Capacity:	HC	75,000	84,000	79,500	177,000		
Medium	SC	374,850	374,850	384,000	349,200		
Setup:	TC	463,850	473,850	477,000	544,200		
1 High	MC2	13,910	15,070	13,760	18,460		
2 Low	HC2	92,743	78,633	118,700	191,449		
t^{pr}/t^{cr}: High	SC2	374,714	374,554	382,993	346,941		
c^{pr}/c^{cr}: Low	TC2	481,367	468 257	515,453	556,850		
$\alpha, \beta = 2$	SL	95.63	97.42	95.11	90.35		

Table IV.
Computational results

(*continued*)

Case	Perf	General	Cyclical maintenance $nk = 1$	$nk = 2$	$nk = 3$	$nk = 4$	$nk = 6$
Case 6	MC	135,000	150,000	135,000	180,000	255,000	Infeasible
Capacity:	HC	47,250	49,500	47,250	82,500	79,875	
Medium	SC	401,400	401,400	401,400	374,850	384,000	
Setup:	TC	583,650	600,900	583,650	637,350	718,875	
1 High	MC2	130,500	148,400	136,100	182,800	258,800	
2 Low	HC2	40,975	68,292	53,881	73,093	117,390	
t^{br}/t^{cr}: Low	SC2	401,400	401,400	401,341	374,791	383,740	
c^{br}/c^{cr}: High	TC2	572,875	618,092	591,322	630,684	759,930	
$\alpha, \beta = 2$	SL	98.45	98.85	98.33	96.73	95.23	
Case 7	MC	22,017	20,709	22,671	30,200	40,068	Infeasible
Capacity	HC	76,584	92,319	84,451	137,489	210,652	
Medium	SC	366,300	374,850	392,550	344,850	362,100	
Setup	TC	464,901	487,878	499,672	512,539	612,820	
1 High	MC2	22,250	21,240	23,260	30,900	40,010	
2 Low	HC2	80,219	41,321	83,371	156,257	286,655	
t^{br}/t^{cr}: Low	SC2	366,214	374,702	392,492	344,642	361,257	
c^{br}/c^{cr}: Low	TC2	468,683	437,263	499,123	531,799	687,922	
$\alpha, \beta = 1.5$	SL	96.88	98.79	96.96	93.78	91.57	
Case 8	MC	220,174	207,093	226,715	301,992	400,680	Infeasible
Capacity	HC	76,584	92,319	84,451	137,498	210,652	
Medium	SC	366,300	374,850	392,550	344,850	362,100	
Setup	TC	663,058	674,262	703,716	784,340	973,432	
1 High	MC2	216,200	204,500	224,500	298,500	392,200	
2 Low	HC2	62,754	34,744	93,190	164,265	321,568	
t^{br}/t^{cr}: Low	SC2	366,172	374,791	392,542	344,744	361,168	
c^{br}/c^{cr}: High	TC2	645,126	614,035	710,232	807,509	1,074,936	
$\alpha, \beta = 1.5$	SL	97.45	98.8	97.08	93.79	91.92	

Table IV.

We evaluate the general preventive maintenance policy and the cyclic maintenance policy for $nk = 1$, 2, 3, 4, 6, which means preventive maintenance is executed every month, every two months, and so on. We evaluate both policies for some different cases and the results are tabulated in Table IV and 5. For each case, we first solve the aggregate production problem and calculate the total costs (TC), which include the maintenance cost (MC), holding cost (HC) and setup cost (SC). At the detailed level, we simulate the realization of machine breakdown (number of run = 100), where each run consists of 12 months (one year). We solve the problem at the detailed level using a rolling horizon approach, i.e. we only solve the first period of the problem and then move to the next period. We calculate the average of the total costs at the detailed level (TC2), which include the maintenance cost (MC2), holding cost (HC2) and setup cost (SC2). At this detailed level, we also measure the service level (SL), which is defined as the fraction of item demand met from the inventory or productions. This service level is calculated as the quantity item demand met from inventory or productions divided by the quantity of total item demand times 100 per cent.

The base case (case 2) shows the problem with medium capacity, high setup cost in machine 1 and low setup costs in machine 2, low maintenance duration and low maintenance cost for both machines. The value for both scale and shape parameters of the machine's failure distribution is 2. We use case 2 as the base case because it resembles the most with our real life application where capacity is mostly at the medium level. In this case, the general maintenance model gives better results than cyclical maintenance models. Although the cyclical model with $nk = 2$ provides the minimum maintenance costs, the minimum total cost is given by the general model. In most of the case, the realization of costs at the detailed level is higher than the expected costs at the aggregate level. Note that the increase of real costs is mainly due to the increase of real holding costs (i.e. the maintenance costs and the setup costs are almost the same). At the detailed level, the real holding costs increases because we take into account the realization of machine breakdowns. When a machine breaks down, the capacity is reduced which makes it harder to obtain a perfect disaggregation. In other words, the item production is limited by the capacity; hence some of the items are stored in the form of work-in-progress inventories. Therefore, when capacity is limited we cannot have a 100% service levels. In term of service level, the general model performs equally well with cyclical maintenance models for $nk = 1$ or $nk = 2$. For the cyclical maintenance, a large value of nk performs worse than the general model both in term of costs and service levels.

The effect of capacity can be seen in case 1 and case 3. When capacity is very loose (see case 1), the holding costs are zero and setup occurs every time a production is needed. There is no or little effect of machine breakdowns because demand can always be filled from an abundant extra capacity. Hence, the service levels can achieve 100 per cent (note that the only uncertainty comes from machine breakdowns). However, when the size of maintenance cycle is very big ($nk = 6$), the chance of machine breakdowns is getting bigger at the end of the maintenance cycle because machines deteriorate progressively. Hence, a 100 per cent service level cannot be achieved if the cycle size is very big. When capacity is very tight (see case 3), both total cost and service level deteriorate for the general model as well as the cyclical maintenance models. The increase holding costs contributes mostly to the increase of the total costs. As expected, the service level is also low when the capacity is very tight. The cyclical maintenance model with $nk = 1$, however, performs better than the other model when the capacity is very tight both in term of service levels and total costs. We can conclude that a monthly preventive maintenance gives a constant and stable (although tight) level of capacity, which makes sure a proper disaggregation at the detailed level. Some policies in the cyclical models are not feasible (see $nk = 4$ and $nk = 6$) when the capacity is very tight.

The effect of capacity can be seen in case 1 and case 3. When capacity is very loose (see case 1), the holding costs are zero and setup occurs every time a production is needed. There is no or little effect of machine breakdowns because demand can always be filled from an abundant extra capacity. Hence, the service levels can achieve 100 per cent (note that the only uncertainty comes from machine breakdowns). However, when the size of maintenance cycle is very big ($nk = 6$), the chance of machine breakdowns is getting bigger at the end of the maintenance cycle because machines deteriorate progressively. Hence, a 100 per cent service level cannot be achieved if the cycle size is very big. When capacity is very tight (see case 3), both total cost and service level deteriorate for the general model as well as the cyclical maintenance models. The increase holding costs contributes mostly to the increase of the total costs. As expected,

the service level is also low when the capacity is very tight. The cyclical maintenance model with $nk = 1$, however, performs better than the other model when the capacity is very tight both in term of service levels and total costs. We can conclude that a monthly preventive maintenance gives a constant and stable (although tight) level of capacity, which makes sure a proper disaggregation at the detailed level. Some policies in the cyclical models are not feasible (see $nk = 4$ and $nk = 6$) when the capacity is very tight.

The effect of setup costs is seen in case 4 where the setup cost at machine 1 is also low. In term of total costs, the general model performs better than the cyclical maintenance models. In term of service levels, however, it is slightly worse than the cyclical maintenance models. Note that in this case, the realization of holding cost at the detailed level is smaller than the expected holding cost at the aggregate level for the general model and cyclical models with $nk = 1$ and $nk = 2$. The effect of maintenance duration (see case 5) is similar to that of the effect of capacity (see case 3). Long maintenance duration tighten the capacity, which makes some cyclical model infeasible to solve (i.e. $nk = 4$ and $nk = 6$). The cyclical maintenance model with $nk = 1$ also gives better-detailed costs than the general maintenance model because it gives a constant level of capacity. The effect of maintenance cost (see case 6) clearly shows that when maintenance cost is high, the general model performs superior than cyclical maintenance models for $nk = 1$ or $nk = 2$. In term of service levels, however, there is no significance difference between the general model and cyclical maintenance models for $nk = 1$ or $nk = 2$. Case 7 and case 8 show the effect of the parameter of failure distribution. A smaller parameter ($\alpha, \beta = 1.5$) means that the machines deteriorate progressively faster than a high value of the machine parameters (see case 2, $\alpha, \beta = 2$). The effect tightens the capacities similar to the effect of tight capacity (see case 3) and the effect of maintenance duration (see case 5). Even when maintenance costs are high (see case 8), the effect of parameter α, β is still very strong. In term of service levels, the monthly maintenance model ($nk = 1$) performs superior than the general model in this case.

In term of costs, the general model always performs better than the cyclical maintenance if the maintenance model is executed independently. A separate cyclical maintenance planning gives a solution with the minimum maintenance cost, i.e. to perform preventive maintenance action every tqo months ($nk = 2$). In the realization of costs (at detailed level), the general model is in average 6 per cent less costly than the maintenance model with $nk = 2$. In term of service level, however, there is no significance difference between the general model and the maintenance model with $nk = 2$.

We implement all models using ILOG OPL 5.0/CPLEX 10.1 on a 3 GHz CPU and 1GB RAM processor. Our illustrative examples consist of five product families, ten items for a 12-periods production planning. It takes less than five minutes to obtain optimal results for the aggregate planning and less than ten minutes to obtain results for the detailed planning using the scenario based optimization model. Since we are working with average capacities, the resulted model at the aggregate level is basically a deterministic case, which can be solved within minutes. At the detailed level, we only implement the solution for the first period. Furthermore, the models are independent for each machine, which give results in a reasonable computational time. Although we use scenario based optimization models, the number of scenarios is still limited because of the Poisson process of failures and the maximum number of failures as given by $N_m^{\max}$ (1).

Conclusion and further research

This study investigates the integration of maintenance planning and hierarchical production planning for multi-stage production systems. A two-level planning is proposed to address the hierarchical planning problem, i.e. aggregate planning and detailed planning. It is assumed that the capacities of machines progressively decline due to deteriorations. Two types of maintenance actions, i.e. preventive maintenance and corrective maintenance are integrated into the hierarchical production planning. The preventive maintenance is integrated into the aggregate production planning, while machine breakdowns, which require corrective maintenance actions, are investigated in the detailed planning. We also propose a general policy for the preventive maintenance planning where maintenance periods do not necessarily fall at equally distant epochs (i.e. there is no fixed cycle size). At the aggregate level, we propose a mixed integer linear programming using aggregate data, such as expected values of capacities and costs. At the detailed planning, the family production is disaggregated into items with the objective to synchronize the run out time of the family inventories and the run out time of the items belonging to the corresponding family. In doing so, we are maximizing the chance of saving some setup costs in the future periods. We propose a scenario-based optimization model given that the number of failures for each machine is stochastic following a Poisson distribution. A weighted multi-objective function is proposed to simultaneously minimize the expected absolute deviation of run out time and the expected unmet production due to machine breakdowns.

We evaluate two approaches of preventive maintenance planning, i.e. a general policy and a cyclical policy. The general model gives better solutions in term of cost than the cyclical maintenance if the maintenance model is executed separately ($nk = 2$). In term of service levels, however, both models perform the same with average service levels equals to 97.6 per cent. Although the monthly maintenance model ($nk = 1$) gives a higher value of costs at the aggregate level, the service levels are 1 per cent better than the general model. The effect of tight capacity, long maintenance duration and small machine parameters similarly tighten the capacity which shows that a stable capacity is more beneficial to achieve a better service level.

Further research is directed towards the investigation of a safety capacity strategy. At the aggregate level, we use the value of average capacities obtained from an optimal production and preventive maintenance planning. The scenario of machine breakdowns naturally varies from the average. Thus, a machine's progressive deterioration may cause significant reductions to the available capacity. We believe that a safety capacity will be able to dampen some of these variations at the aggregate level. We need to further investigate the amount of safety capacity needed at the aggregate level such that the realization of machine breakdown can be resolved effectively at the detailed level. Another direction for future research is the inclusion of uncertain demand into the model.

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About the authors

Carles Sitompul finished his Bachelor's and Master's studies from the Bandung Institute of Technology (ITB), Indonesia. He also holds an advanced Master's degree from the Center of Industrial Management, Katholieke Universiteit Leuven (Belgium) in 2005. Then, he continued his study at Ghent University where he received his Doctor in Engineering with major in industrial management and operations research in 2010.

El-Houssaine Aghezzaf holds a PhD in Applied Mathematics from the Center of Operations Research and Econometrics of the Université Catholique de Louvain (UCL), Belgium. He is currently Professor of Operations Research and Industrial Engineering, and also Head of the Department of Industrial Management in the Faculty of Engineering of Ghent University (UGent), Belgium. His research focus is mainly in the design and management of robust supply chains, production planning, and scheduling in a stochastic environment. El-Houssaine Aghezzaf is the corresponding author and can be contacted at: elhoussaine.aghezzaf@ugent.be