Integrated Production and Maintenance Planning: A Comparison Between Block Policies

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Abstract

The traditional production and maintenance planning models have been separately well documented, and much work was done to improve them. However, the integrated production and maintenance planning model emerged recently, and firms highly desire it due to its ability to ease the production process by including maintenance activities from the beginning of the planning horizon. In this paper, we present an integrated production and maintenance planning model. We compare the two block maintenance policies (as bad as old and as good as new). The results show that preventive maintenance is less frequent when using block-AGAN compared to ABAO, while the maintenance and production costs are higher.

Keywords
Production, Maintenance, Block Policy, Optimization

1. Introduction

The increased demand for products forced industrialists to develop models that satisfy this demand with the lowest possible cost. This requires companies to pay great attention to their machines used in the production processes and on their characteristics, i.e., their capacity, availability, suitability to social issues, reliability, and lifetime. Production workshops, by their nature, are subject to events such as the arrival of new tasks to be performed by the machines or to machine break-down (Bouzidi-Hassini, Benbouzid-Si Tayeb, Marmier, & Rabahi, 2015). They are responsible for proceeding to produce the new orders and make sure the required amount will be delivered within the specified period. Therefore, industrialists must develop planning models that account for these events.

Production planning allocates the existing resources such as employees, materials, and machines to the production activities in order to serve different customers. Production planning is done for a specific level of a duration of time called the planning horizon. It determines the amounts to produce and the level of capacity to satisfy the demand in every period of the planning horizon. Moreover, it can relate the required production level with the available resources. It also schedules the setups and deliveries of production orders (Taylor & Saad, 2007). Production planning models aim to use the production equipment to the maximum in order to satisfy the demand in a specified period of time while neglecting the unavailability periods.

On the other hand, maintenance aims to perform planned and routine actions that prevent the production system from failures, which cause a stoppage in production planning, known as preventive maintenance (Yang, Ma, Peng, Zhai, & Zhao, 2017). Moreover, the type of maintenance actions that deal with a sudden machine failure is called corrective maintenance. The aim of this type of maintenance is to restore the system to a particular condition after a breakdown occurs so that the work can resume (Wang, Deng, Wu, Wang, & Xiong, 2014). The types of maintenance policies can, therefore, be classified into two types: reactive that corresponds to the corrective actions and proactive that corresponds to the preventive actions, and that can be divided into time-based and condition-based maintenance policies.

While following the reactive based maintenance policy, the equipment runs until it breaks down or fails. It is an efficient policy, as the component will be fully utilized when it fails. Once a component fails, this will create an unscheduled maintenance task, which will result in an unscheduled replacement and labor cost which will limit the selection of this type of policies to systems that are typically not expensive and have a lower risk at stoppages and break downs (Sherwin, 2001).

The proactive maintenance consists of two policies: time-based and condition-based. Under the time based maintenance policy, the age policy stipulates that the components renewal happens either when they fail or when they reach the end of their lifecycle whichever occurs first while the block policy requires that the preventive renewals happen at fixed intervals in time and cannot be changed due to failures that occur within the planning horizon. When a failure occurs, the component can be either restored to as good as new (AGAN) status where the component starts its new lifecycle or restored to as bad as old (ABAO) where the component runs starting from the point just before failure and is assumed to continue its life cycle (Sherwin, 2001). The decision to select which type depends on many factors like machine remaining life cycle and replacement and operating costs. A well-structured model must be developed to give the best decision regarding policy selection.

In condition-based maintenance, the decision of repair depends on the state (health) of the system, where sensors and signs can determine whether to restore the system to AGAN or to do minimal repairs (Bouzidi-Hassini et al., 2015). This type of maintenance is very effective since it can tell you about the remaining life of the part and warn you so replacements will be applied only on necessary parts, which can minimize parts cost.

Fakher and Nourelfath (2015) found that production planning, maintenance scheduling, and design of quality systems in the production units have been treated separately despite the strong links between them. Nowadays, many researchers have proposed integrated models for both production and maintenance. Moreover, Fitouhi and Nourelfath (2012) stated, there must be a collaboration between maintenance and production departments to guarantee success for modern companies. They added that the relationship might become conflictual. Since the same equipment is shared between both departments where the production department has to satisfy customer demands within promised delays, which push for the maximal use of the production equipment and the maintenance departments should perform preventive actions for this equipment to keep them working smoothly. Therefore, an integrated model helps effectively in smoothing the production process since the maintenance decisions are considered from the beginning which will help in organizing the production process since maintenance actions are already known and included. This information sharing not only helps in making effective decisions but also fits in the context of Industry 4.0, where Industry 4.0 concept for production lines has machines equipped with monitoring technologies to facilitate maintenance tasks (Mourtzis, Vlachou, Zogopoulos, & Fotini, 2017).

In this paper, we present an integrated production and maintenance planning model using optimization. Using this model, we compare the two block polices, i.e., AGAN and ABAO, to illustrate the effect of using different policies on the production plan.

The organization of this paper is as follows. Section 2 presents the literature on relevant topics. Section 3 presents the mathematical model formulation. Section 4 compares the two block policies using a numerical example. Section 5 concludes the paper.

2. Literature Review

In this section, we divide the relevant work into three parts. The first part reviews the work done in production planning only. The second part reviews the work done on maintenance planning only, and the last part presents the work that integrated production and maintenance planning.

2.1 Production planning models

Production planning models have been considered extensively in the literature; for instance, Woo and Ki (2016) studied the production-inventory system with Markovian service queue and developed a cost model from the mean performance measures. Li et al. (2016) developed a mixed-integer linear programming model for integrated production inventory routing planning for the food industry while accounting for quality aspects and maximizing the profit. Dev et al. (2017) considered manufacturing and remanufacturing strategies in closed-loop production and inventory planning systems using discrete event simulation. In the discrete event simulation, they considered two policies that are continuous and periodic, with consideration of the total recoverable and serviceable, manufacturing lead times, and remanufacturing lead time. Manna, Dey and Mondal (2017) studied imperfect production system with advertisement and time-dependent demand and economic production quantity model. In their model, the inspection rate was not constant, the screening rate and the production rate were not equal, the production rate was variable, and defective rate and deterioration rate dependence on production rate.

2.3 Maintenance Planning

Many researchers proposed maintenance scheduling models to deal with production equipment breakdowns. Regattieri et al. (2015) studied different maintenance policies on several critical components for the A320 aircrafts using simulation and optimization while focusing on cost and availability. They have also studied the issue of spare parts inventory. The proposed framework consists of data collection, failure process modeling, and preparation process model, which corresponds to the first stage. In the second stage, consideration of condition monitoring, and preventive maintenance intervention cost, purchase cost of critical components and system down-time cost to be inputs for the complex system model. The last stage in the framework includes consideration of spare parts storage cost and supply condition of the component in the complex system modeling to determine the best mix of maintenance policies and optimal stock level of spare parts. Lim, Qu and Zuo (2016) studied another variant of age replacement policy that suggests Bayesian imperfect repair with random probability instead of minimal repair or perfect repair. Imperfect repair policy combines both perfect repair and minimal repair with a random probability. They develop a cost per unit time function based on an infinite-horizon and one-replacement cycle. Moreover, Chalabi et al. (2016) presented an optimization model for preventive maintenance work for multi-series production systems. Their optimization model that deals with preventive maintenance duration for each unit and imperfect maintenance model and it is implemented using particle swarm optimization (PSO) and will improve the availability and minimize the preventive maintenance cost. Rebaiaia et al. (2016) compared two basic periodic strategies age and block to conclude which one is better for industrialists. Their numerical analysis showed that block maintenance strategy is slightly better. Ade et al. (2017) proposed a maintenance optimization model for offshore wind farms that finds the best scheduling for maintaining the turbine of these winds. They took into account multiple vessels, periods, and operations. Yang et al. (2017) proposed a preventive maintenance policy for a single unit system that might fail due to unexpected breakdown or internal deterioration. This model aims to minimize cost per unit time and aims to determine the preventive maintenance interval, inspection interval, and the number of inspections done. The model was verified on an oil pipeline system.

2.3 Integrated Production and Maintenance Planning

Weinstein and Chung (1999) presented a three-part model for integrated maintenance and production decisions where the first two stages are used to deal with the production part. An aggregate production plan using linear programming is generated, and a master production schedule is developed to minimize the weighted deviations. The third stage is work loading center requirements that used to simulate equipment failures during the aggregate production planning horizon. Aghezzaf, Jamali and Ait-Kadi (E. H. Aghezzaf, Jamali, & Ait-Kadi, 2007) studied capacitated production and maintenance problems in a finite planning horizon. They aimed to find a preventive maintenance strategy and lot-sizing that satisfies a deterministic demand by minimizing the total production and maintenance cost in the planning horizon. They assumed random failure in the production system and every maintenance action reduces the system capacity. They also assumed that there would be no backlogging and they used minimal repair strategy (block ABAO). Moreover, Aghezzaf and Najid (2008) studied the issue of integrating the production planning and preventive maintenance in manufacturing production systems. They considered the system that composed parallel failure-prone production lines. They assumed that a minimal repair would be applied to restore the system to an as-bad-as-old condition when a failure occurs. They assumed that the available time is reduced whenever maintenance action occurs. Kenne and Nkeungoue (2008) Dealt with the control of corrective and preventive maintenance in a production system. Both preventive and corrective maintenance policies are related to the machine age, where the corrective is to give minimal repair for the system to function.

Moreover, Nourelfath and Châtelet (2012) proposed a multi-state model that considers jointly preventive maintenance and production planning in multiple parallel machine system, where the planning problem is a multi-product capacitated lot-sizing problem. Machani and Nourelfath (2012) Implemented an integrated production planning model where they have a multi-state production system with binary-state components. They presented a Variable Neighborhood Search (VNS) in their model that deals with the preventive maintenance selection task. Where VNS is a metaheuristic used to solve problems in which a systematic change of neighborhood within a local search is carried out. Both preventive and corrective maintenance actions will be performed on each component of the multi-state system. Their aim is to minimize the total expected cost using the integrated model. Fitouhi and Nourelfath (2012) integrated the preventive maintenance with tactical production in a multistate system. They suggested a maintenance policy that is not cyclical for its preventive repairs and it is for each component of the system where these actions can be carried at the beginning or during the planning period to restore the system to as-bad-as-old status. The model minimizes preventive, setup, holding, backorders and production costs.

Furthermore, Yalaoui, Chaabi and Yalaoui (2014) presented an integrated production and preventive maintenance model using mixed-integer linear program. In addition to multi-lines, multi-periods, and multi-items, they considered the system deterioration as a capacity reduction. Both preventive and corrective maintenance polices are intended to restore the system to an as-good-as new status. Bouzidi-Hassini et al. (2015) proposed an approach that integrates production and maintenance planning taking into account human resources, spare parts availability and the last operating duration of the machine to apply condition-based preventive maintenance. Aghezzaf, Khatab and Tam (2016) investigated the issue of integrating production and maintenance planning in a failure-prone manufacturing system. They assumed that the system could be preventively maintained at planned periods. They also assumed that the preventive maintenance in their system would lie between as bad as old and as good as new, and only overhauling will bring the system back to an as-good-as new status. They took the system manufacturing capacity and operational reliability state into consideration. The planning integration is carried out at the tactical level, which can help in planning the required production and preventive maintenance tasks. The actual scheduling will be carried out at the operational level.

2.4 Research Gap

Previous works considered either production planning models or maintenance planning models. The work on the integrated production and maintenance planning model is limited. Moreover, previous works studied on maintenance policy in the production planning models, while the choice of the maintenance policy depends on decision-makers. In this work, we compare between the two block policies when used in the production planning modelling.

3. Mathematical model

In this section, we present the integration production and maintenance planning model for the two-block policies. This model is based on the work of (E. H. Aghezzaf et al., 2007), which uses block ABAO policies. We show how this model can be modified to account for the block AGAN policy.

3.1 Sets

- $\boldsymbol{T}$: Set of periods in the planning horizon, indexed by $t = 1$,..., T.
- $\boldsymbol{P}$: Set of products to be produced in the planning horizon, indexed by p.

3.2 Parameters

- D_{tp}: Demand for product p in period t.
- $C(t)$: Capacity in period t based on the machine availability.
- C: Maximum capacity of the production machine in each period.

- F_{pt} ,V_{pt}: Fixed cost and variable cost of production product p in period t, respectively.
- h_{pt}: Holding cost of one product p by the end of period t.
- PT_p: Processing time of product p.
- S: A very big number.
- CM: Cost of performing a preventive maintenance.
- CF: Cost of performing a corrective maintenance in block-AGAN policy (replacing with a new component upon failure).
- CR: Cost of performing a corrective maintenance in block-ABAO policy (repairing a failed component).
- TM: Time required to perform a preventive maintenance
- TF: Time needed to replace a failed component in block-AGAN policy.
- TR: Time needed to repair a failed component in block-ABAO policy.
- $N(t)$: The expected number of failures in the block-AGAN policy.
- $r(t)$: The hazard rate in the block-ABAO policy.

3.3 Decision Variables

- Q_{pt}: Quantity of product p produced in period t.
- I_{pt}: The amount of inventory stored at the end of period t from product p.
- Y_{pt}: A binary variable stated if product p is produced in period t ($Y_{pt} = 1$) or not ($Y_{pt} = 0$).
- M: The preventive maintenance cycle.

3.4 Model

$$Minimize\ Z = \sum_{t\in\mathcal{T}}\sum_{p\in P}⟦\left(F_{pt}Y_{pt} + V_{pt}Q_{pt} + h_{pt}I_{pt}⟧\right) + T\left(\frac{CM + CF \times N(M)}{M}\right) \quad (1)$$

Subject to

$$I_{pt} = Q_{pt} + I_{pt-1} - d_{pt}, \qquad \forall p \in P, t \in \mathcal{T}, \quad (2)$$

$$Q_{pt} \leq SY_{pt}, \qquad \forall p \in P, t \in \mathcal{T}, \quad (3)$$

$$\sum_{p\in P} PT_P \times Q_{pt} \leq C(t),\ \ \forall t \in \mathcal{T}, \quad (4)$$

$$Q_{pt}, I_{pt} \geq 0, \qquad \forall p \in P, t \in \mathcal{T}, \quad (5)$$

$$Y_{pt} \in \{0,1\}, \qquad \forall p \in P, t \in \mathcal{T}, \quad (6)$$

The objective function (1) minimizes the total production and maintenance costs. The first part represents the fixed production, variable production, and inventory holding costs. The second part calculates the maintenance cost as the unit maintenance cost in the block-AGAN policy multiplied by the duration of the planning horizon.

Note that objective function (1) is replaced by the following one for the block-ABAO policy as in (E. H. Aghezzaf et al., 2007).

$$Minimize\ Z = \sum_{t\in\mathcal{T}}\sum_{p\in P}⟦\left(F_{pt}Y_{pt} + V_{pt}Q_{pt} + h_{pt}I_{pt}⟧\right) + T\left(\frac{CM + CR \times \int_0^M r(u)du}{M}\right) \quad (7)$$

Constraint (2) calculates the available inventory at the end of each period for each product and ensures that the demand for that period is satisfied as the inventory can be either zero or a positive value. Constraint (3) links the variables Q_{pt} with the binary variable Y_{pt} so that whenever a quantity is produced, the fixed cost is calculated. Constraint (4) ensures that the total time needed to process all quantity produced is within the machine capacity. The machine capacity in terms of time depends on the availability and thus on the maintenance schedule. The detailed calculation of the capacity is explained below. Constraint (5) is the non-negativity constraint, and Constraint (6) ensures that Y_{pt} is a binary variable.

The presented model is non-linear. Thus, it is first transformed to a linear model by assuming that a maintenance period M can happen in k multiple of periods. By doing so, we can discretize the value of M and iterate to solve the linear model. $NI = \lfloor T/k \rfloor$. The updated objective function and capacity constraint can be re-written as follows:

<u>For block-ABAO </u>(E. H. Aghezzaf et al., 2007)<u>:</u>

$$Minimize\ Z = \sum_{t\in\mathcal{T}}\sum_{p\in P}[\![(F_{pt}Y_{pt} + V_{pt}Q_{pt} + h_{pt}I_{pt}]\!]) + \sum_{n=1}^{NI} CM + \left(\sum_{t=(n-1)k+1, t\leq T}^{nk} CR \times \int_0^1 r\big(u + (t-(n-1)k-1)\big)du\right) \quad (8)$$

$$C(t) = \begin{cases} C - TM - TR \times \int_0^1 r(u)du, & t = (n-1)k+1 \\ C - TR \times \int_0^1 r\big(u + (t-(n-1)k-1)\big)du, & (n-1)k+1 \leq t \leq nk \end{cases}, \quad (9)$$

<u>For block-AGAN:</u>

$$Minimize\ Z = \sum_{t\in\mathcal{T}}\sum_{p\in P}[\![(F_{pt}Y_{pt} + V_{pt}Q_{pt} + h_{pt}I_{pt}]\!]) + \sum_{n=1}^{NI} CM + \left(\sum_{t=(n-1)k+1, t\leq T}^{nk} CF \times \big(N(t-(n-1)k) - N(t-1-(n-1)k)\big)\right) \quad (10)$$

$$C(t) = \begin{cases} C - TM - TF \times N(1), & t = (n-1)k+1 \\ C - TR \times \big(N(t-(n-1)k) - N(t-1-(n-1)k)\big), & (n-1)k+1 \leq t \leq nk' \end{cases} \quad (11)$$

4. Numerical example

Let us assume a planning horizon of 20 periods. Two products (A and B) are to be produced using one machine with a maximum nominal capacity of $C = 15$. Table 1 shows the fixed cost, variable cost, and holding cost for each product. The demand for each product in each period is given in Table 2. Machine failure is assumed to follow a gamma distribution with a shape parameter of 2 and a scale parameter of 1. The machine scheduled preventive maintenance costs are equal to $CM = 28$, its minimal repair costs $CR = 75$, and replacing it with a new one upon failure costs $CF = 110$. The maintenance time TM, failure time TF, and repair time TR are 1, 14, 9, respectively. The processing time for each product is 1. The model is implemented and solved using MATLAB R2017a.

Table 1: Fixed, variable and holding costs for products A and B.

Product	Fixed cost	Variable cost	Holding cost
A	25	5	2
B	25	5	2

Table 2: Demand for product A and B in each period in the planning horizon

Product	Period																			
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
A	2	3	2	3	2	3	2	3	2	3	2	3	2	3	2	3	2	3	2	3
B	3	2	3	2	3	2	3	2	3	2	3	2	3	2	3	2	3	2	3	2

Table 3 shows the optimal production, maintenance and total costs for each preventive maintenance scenario. In the block-AGAN, the lowest maintenance cost appears when performing preventive maintenance every ten periods, while in block-ABAO, it recommends performing preventive maintenance once in every four periods. In both policies, the total production costs start in the scenario where preventive maintenance is performed every period. The total cost is minimum when performing preventive maintenance every six periods in the AGAN, while for the ABAO it suggests performing it every two periods. Tables 4 shows the optimal production plan for the optimal maintenance period using block-AGAN and block-ABAO. Both policies produce the same production plan, which has the minimum production cost.

Table 3: Optimal production, maintenance and total costs for each maintenance scenario

K	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**

	Block-AGAN									
TMC	588.8	548.1	543.0	541.3	540.3	539.7	539.3	538.9	538.7	**538.5**
TPC	**529.0**	529.0	529.0	534.0	534.0	529.0	534.0	534.0	534.0	534.0
TC	1117.8	1077.1	1072.0	1075.3	1074.3	**1068.7**	1073.3	1072.9	1072.7	1072.5
	Block-ABAO									
TMC	510.1	**478.0**	496.8	518.2	537.2	553.4	567.2	579.0	589.2	598.2
TPC	**529.0**	529.0	529.0	534.0	531.1	529.0	534.0	538.2	538.2	538.2
TC	1039.1	**1007.0**	1025.8	1052.2	1068.3	1082.4	1101.2	1117.2	1127.4	1136.3

TMC = Total maintenance cost
TPC = Total production cost
TC = Total cost

Table 4: Optimal production schedule using block-AGAN policy with K = 6 and block-ABAO policy with K = 2

Period	Product A		Product B	
	Quantity	Inventory	Quantity	Inventory
1	2	0	8	5
2	8	5	0	3
3	0	3	0	0
4	0	0	7	5
5	7	5	0	2
6	0	2	0	0
7	0	0	10	7
8	8	5	0	5
9	0	3	0	2
10	0	0	0	0

5. Conclusion

In this paper, we presented an integrated production and maintenance planning model for block policies, block-AGAN, and block-ABAO. The model is formulated as non-linear and then transformed into a linear one by discretizing the maintenance period. Based on our results, using Block-AGAN in production planning requires having preventive maintenance in a less frequent manner than block-ABAO. However, the maintenance and production costs are higher.

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Biographies

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