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 $t = 1,\ldots,$ 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

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

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).

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

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:

For block-ABAO (E. H. Aghezzaf et al., 2007):

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

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

<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.

Acknowledgements

This work was supported by the University of Sharjah [grant numbers 1702040576-P and 1602040538-P].

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