Optimal production plan for a multi-products manufacturing system with production rate dependent failure rate

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This study deals with the problem of dependence between production and failure rates in the context of a multi-product manufacturing system. It provides an answer about how to produce (i.e. the production rates) and what to produce (i.e. which product) over a finite horizon of \( H \) periods of equal length. We consider a single randomly failing and repairable manufacturing system producing two products \( P_a \) and \( P_b \). The product \( P_a \) is produced to supply the strategic demand \( d(k) \) of the principal customer via a buffer stock \( S \) over \( k \) periods \( (k = 1, 2, \ldots, H) \). The second product \( P_b \) is produced to meet a secondary but very profitable demand. It is produced during a given interval at the end of each period \( k \). We develop a genetic algorithm to determine simultaneously the optimal production rate of the first product during each period \( k \) and the optimal duration of the production interval of the second product, maximising the total expected profit.

Keywords: production control; failure rate; inventory; multi-products; genetic algorithms

1. Introduction

Production systems are submitted to uncertainties and disturbances like demand rates or failures. In this context, there has been increasing interest to study maintenance policies and production control strategies under a joint approach integrating maintenance and production control. This approach has been studied in Boukas et al. (1990), Srinivasan and Lee (1996), Gharbi and Kenne (2000) and Dahane et al. (2008), etc. These studies propose a joint optimisation of maintenance management and production control.


In this study we consider the production control and failures rate of the production unit under a joint approach. Some studies have examined the relationship between production rates or plan and failures rates.

Martinelli (2005) studied a manufacturing system with a single machine producing a single product and a finite capacity inventory, with failure rate depending on the production rate. The author considered a machine characterised by a Markov failure/repair process with two different failure rates, one for low and one for high production rates. Liberopoulos and Caramanis (1994) studied the optimal flow control of single product production systems with production rate dependent failure rates. Dahane et al. (2009) were interested in the dependence between failure and production rates, under uncertainties related to the stock level. They developed a mathematical model to determine the optimal production plan.

In this work, we study the problem of a production plan for a multi-products manufacturing system, when the failure rate depends on the production rate. The objective is to determine the optimal production plan over a finite horizon maximising the generated profits.
The rest of the paper is organised as follows. The next section presents the considered system, notations and working assumptions. In Section 3 we develop the mathematical model, based on expressions of generated costs and revenues. Section 4 is dedicated to the numerical procedure and the solving genetic algorithm. Summary and conclusion are provided in Section 5.

2. Notations and working assumptions

The considered multi-products manufacturing system consists on a randomly failing machine $M$. Machine $M$ can operate with a maximum production rate $U_{\text{max}}$ to produce a product $P_a$ to supply the demand $d(k)$ at the end of each period $k$ of the production plan ($k = 1, \ldots, H$). This product $P_a$ is considered as the strategic product of the principal customer under a long term client–customer relationship.

In order to maximise the utilisation of the machine’s production capacity it was decided to expand the manufacturing system activities to a new segment, by producing another product, $P_b$, more attractive and more profitable.

In this study, the plan horizon is divided into $H$ periods with the same length $\Delta t$ (Figure 1). During each period the production of $P_a$ is performed over the interval $\Delta P_a$ ($\Delta P_a < \Delta t$).

The product $P_b$ is produced at the end of each period, during the interval $\Delta P_b$ ($\Delta t = \Delta P_a + \Delta P_b$) (see Figure 1).

We consider dependence between the production and failure rates, such as the failure rate $\lambda_s(t)$ during each period $k$ ($k = 1, 2, \ldots, H$) depends on the production rate $U(k)$. So, the production at high rate accelerates the machine degradation and therefore increases the number and the total cost of repairs. But producing at low rates contributes to an increase of the probability to incur losses due to unsatisfied demands (or delays).

Our objective is to determine the optimal production rate $U(k)$ for each period ($k = 1, 2, \ldots, H$) and the optimal duration of the production of the secondary product $P_b$, which maximise the total profit over the plan horizon $H\Delta t$.

The total profit consists of the difference between revenues (including production revenues of each product) and the generated costs of inventory, maintenance, production and delay penalties.

The following notations are used in the formulation:

- $f(\cdot)$ Probability density function associated to machine time to failure.
- $F(\cdot)$ Probability distribution function associated to machine time to failure, such as:
  \[ F(t) = \int_0^t f(x)\,dx. \]
- $\Delta t$ Production period duration.
- $d(k)$ Demand of product $P_a$ during period $k$, $k = 1, \ldots, H$.
- $U(k)$ Production rate during the period $k$, $k = 1, \ldots, H$.
- $U_{\text{max}}$ Maximum production rate.
- $S(k)$ Inventory level of $P_a$, at the end of period $k$, $k = 1, \ldots, H$. $S(0) = 0$.
- $\lambda_{\text{max}}(t)$ Nominal machine failure rate function (with $\lambda_{\text{max}}(0) = 0$).
- $\lambda_s(t)$ Machine failure rate function during period $k$, $k = 1, \ldots, H$.
- $C_a^h$ Holding cost of one product of $P_a$ during one time unit.
- $C_b^h$ Holding cost of one product of $P_b$ during one time unit.
- $C_a^p$ Production cost of one unit of $P_a$.
- $C_b^p$ Production cost of one unit of $P_b$.
- $P_a^r$ Production revenue of one unit of $P_a$.
- $P_b^r$ Production revenue of one unit of $P_b$.

![Figure 1. Production plan horizon.](image-url)
Minimal repair cost.

Shortage cost of one unit of $P_a$ during one time unit.

The total inventory cost over the plan horizon $H\Delta t$.

The total maintenance cost over the plan horizon $H\Delta t$.

The total production cost over the plan horizon $H\Delta t$.

The total delay penalties over the plan horizon $H\Delta t$.

The total production revenue of $P_a$ over the plan horizon $H\Delta t$.

The total production revenue of $P_b$ over the plan horizon $H\Delta t$.

The total production revenue over the plan horizon $H\Delta t$ ($TP = PR_a + PR_b$).

The total profit over the plan horizon $H\Delta t$ ($TP = PR - (IC + MC + PC + DP)$).

The following assumptions are considered:

- Failures are detected instantaneously.
- The repairs duration is negligible in comparison with the total operating duration.
- The produced items are imperishable with time.
- The time to switch production from a product to the other one is negligible.
- During the interval $\Delta P_b$, the machine produces at its maximum rate $U_{\text{max}}$ under a just-in-time configuration, in order to meet the maximum quantity of $P_b$ (there is no buffer stock for $P_b$).
- The demand of product $P_a$ arrives at the end of each period. The average demand on the horizon is lower than the maximum rate of production. But for a given period $i$ ($i = 1, \ldots, H$), we may have a demand $d(i)$ that exceeds the maximum production capacity:

$$\begin{align*}
\forall i = 1, \ldots, H : d(i) & \leq \Delta P_a \cdot U_{\text{max}} \\
\exists i = 1, \ldots, H : d(i) & > \Delta P_a \cdot U_{\text{max}}.
\end{align*}$$

- If the demand is not fully satisfied, the amount recovered is necessarily satisfied during the following period:

$$\frac{d(k)}{U(k + 1)} \leq \Delta P_a \quad \forall k = 1, (H - 1).$$

- At the end of the last period $H$, if the demand is not completely satisfied, then, an additional interval $\Delta T_A$ is required in order to recover the remaining quantity with the maximum production rate $U_{\text{max}}$:

$$\Delta T_A \leq \frac{d(H)}{U_{\text{max}}(k + 1)}.$$ 

- At the end of each period, if the demand is not satisfied, a delay penalty is generated depending on the time required to recover the remaining quantities.
- Production rates can satisfy the overall demand during the production plan:

$$\left(\sum_{k=1}^{H} d(k)\right) \leq \left(H \cdot \Delta P_a \cdot \sum_{k=1}^{H} U(k) + \Delta T_A \cdot U_{\text{max}}(k + 1)\right).$$

3. Mathematical model

Our objective is to determine simultaneously the optimal production rates of $P_a$ during each period $k$ ($k = 1, \ldots, H$) and the optimal duration to produce the secondary product $P_b$, which maximise the total profit.

The total profit is the difference between the generated revenues (of each product) and the generated costs. The expected total cost includes the production cost, the holding cost, the maintenance cost and the delay penalties cost.
3.1 Holding cost

The total holding cost $IC$ includes the inventory cost of each product. For the secondary product $P_b$, the demand is infinite. So the machine operates in a just-in-time configuration with its maximum production rate $U_{\text{max}}$. Consequently, the inventory holding cost for $P_b$ is null ($IC_b = 0$).

The inventory holding cost for $P_a$ is given by the following expression:

$$ IC = IC_a = \sum_{k=1}^{H} C_a^k \cdot Z(k) $$

(1)

$Z(k)$ is the area generated by the inventory level evolution during the period $k$ ($k = 1, \ldots, H$).

The evolution of the inventory level can be expressed as:

$$ S(k) = S(k-1) + U(k)\Delta P_a - d(k), $$

where $S(0) = 0$. So,

$$ S(k) = \sum_{i=1}^{k} (U(i)\Delta P_a - d(i))/S(0) = 0. $$

The generated area during a period is given as follows:

$$ Z(k) = \max(S(k-1), 0)\Delta P_a + \frac{1}{2} U(k)\Delta P_a^2 + (\max(S(k-1), 0) + U(k)\Delta P_a)\Delta P_b $$

$\forall k = 1, \ldots, H$.

Thus,

$$ Z(k) = \max\left(\sum_{i=1}^{k-1} (U(i)\Delta P_a - d(i)), 0\right)\Delta t + \frac{1}{2} U(k)\Delta P_a^2 + U(k)\Delta P_a\Delta P_b. $$

Consequently, the holding cost is expressed as follows:

$$ IC = C_a^0 \sum_{k=1}^{H} \left(\max\left(\sum_{i=1}^{k-1} (U(i)\Delta P_a - d(i)), 0\right)\Delta t + \frac{1}{2} U(k)\Delta P_a^2 + U(k)\Delta P_a\Delta P_b\right). $$

(2)

3.2 Production cost

The production unit produces exactly the requested number of product $P_a$. For the secondary product $P_b$, the machine operates at its maximum production rate $U_{\text{max}}$. Hence, the total production cost is given by the following expression: $PC = PC_a + PC_b$

where

$$ PC_a = C_a^0 \sum_{k=1}^{H} d(k) $$

and

$$ PC_b = C_b^0 (H \cdot U_{\text{max}} \cdot \Delta P_b). $$

Thus

$$ PC = C_a^0 \sum_{k=1}^{H} d(k) + C_b^0 (H \cdot U_{\text{max}} \cdot \Delta P_b). $$

(3)
3.3 Maintenance cost

The expected maintenance total cost is given by the following expression:

\[ MC = C_r \cdot M(H\Delta t). \]

\( M(H\Delta t) \) represents the average number of failures occurring during the production plan

\[ M(H\Delta t) = \sum_{k=1}^{H} \int_{0}^{\Delta t} \lambda_k(t)dt. \]

The \( H \) periods of the production plan are divided in sub-periods in order to distinguish the production intervals of each product \( P_a \) and \( P_b \). Let \( \Delta P_a \) and \( \Delta P_b \) denote the production sub-periods corresponding to each product (see Figure 2).

Note that odd indices \( q \) correspond to production sub-periods of \( P_a \), whereas even indices correspond to those of \( P_b \). Thus, the maintenance cost and the average number of failures can be written as follows:

\[ MC = C_r \cdot M(2H\tau) \]

and

\[ M(2H\tau) = \sum_{q=1}^{2H} \int_{0}^{\tau} \lambda_q(t)dt \]

where

\[ \tau = \begin{cases} \Delta P_a & \text{if } q = 2\gamma - 1 \quad \text{(product } P_a) \\ \Delta P_b & \text{if } q = 2\gamma \quad \text{(product } P_b) \end{cases} \quad |\gamma = 1, H. \]

On the other hand, the relationship between failure rates is given as follows:

\[ \lambda_i(t) = \lambda_{i-1}(\tau) + \frac{U(i)}{U_{\max}} \lambda_{\max}(t) \quad \forall t \in [0, \tau], \ i \geq 1. \]

Thus:

\[ \lambda_i(t) = \lambda_{\max}(0) + \sum_{l=1}^{i} \frac{U(l)}{U_{\max}} \lambda_{\max}(t) \]

but \( \lambda_{\max}(0) = 0 \).

Consequently,

\[ \lambda_i(t) = \sum_{l=1}^{i} \frac{U(l)}{U_{\max}} \lambda_{\max}(t). \]

We distinguish the sub-periods of each product:

\[ \lambda_i(t) = \sum_{m=1}^{i} \frac{U(2m)}{U_{\max}} \lambda_{\max}(t) + \sum_{m=1}^{i} \frac{U(2m-1)}{U_{\max}} \lambda_{\max}(t). \]

\[ \Delta P_a \quad \Delta P_b \]

\[ q=1 \quad q=2 \quad q=i \quad q=i+1 \quad q=2H-1 \quad q=2H \]

Figure 2. Production plan horizon with sub-periods.
Since the machine operates with maximum production rate $U_{\text{max}}$ to produce $P_b$, we have:

$$U(2m) = U_{\text{max}}.$$ 

Thus, the failure rate will be expressed as follows:

$$\lambda_i(t) = \left[ \left[ \frac{i}{2} \right] \right] \lambda_{\text{max}}(t) + \sum_{m=1}^{i} \frac{U(2m-1)}{U_{\text{max}}} \lambda_{\text{max}}(t).$$

Now, the expression of the average number of failure during the production plan is given by:

$$M(2H\tau) = \sum_{q=1}^{2H} \int_{0}^{\tau} \lambda_q(t)dt$$

$$= \sum_{q=1}^{2H} \int_{0}^{\tau} \left( \left[ \left[ \frac{i}{2} \right] \right] + \sum_{m=1}^{q} \frac{U(2m-1)}{U_{\text{max}}} \right) \lambda_{\text{max}}(t)dt.$$ 

Therefore,

$$M(2H\tau) = \left( \sum_{q=1}^{2H} \left[ \left[ \frac{q}{2} \right] \right] \right) + \left( \sum_{q=1}^{2H} \sum_{m=1}^{q} \frac{U(2m-1)}{U_{\text{max}}} \right) \int_{0}^{\tau} \lambda_{\text{max}}(t)dt.$$ 

Finally, the maintenance total cost can be written as follows:

$$MC = C_r \left( \sum_{q=1}^{2H} \left[ \left[ \frac{q}{2} \right] \right] \right) + \frac{1}{U_{\text{max}}} \left( \sum_{q=1}^{2H} \sum_{m=1}^{q} U(2m-1) \right) \alpha$$

where

$$\alpha = \int_{0}^{\tau} \lambda_{\text{max}}(t)dt.$$ 

### 3.4 Delay penalties

Penalties are the consequence of a delay to satisfy all the requested demands of $P_a$. Figure 3 illustrates a delay situation occurred at the end of period $k$. This situation has caused a shortage recovered during the next period $(k + 1)$.

Penalties are calculated according to the required duration $T(\cdot)$ to produce the missed quantity at the end of each period. They are given by the following expression:

$$DP = \sum_{k=1}^{H} C_d \cdot T(k)$$

where

$$T(k) = \frac{\left| \min(S(k), 0) \right|}{U(k+1)}.$$
For the last period $H$, the delay is expressed as follows:

$$T(H) = \min(S(H), 0) / U_{\text{max}}.$$ 

Then,

$$DP = C_d \left( \sum_{k=1}^{H-1} \frac{|\min(S(k), 0)|}{U(k+1)} + \frac{|\min(S(H), 0)|}{U_{\text{max}}} \right).$$

The additional interval $\Delta TA$ (of duration $T(H)$) necessary to recover the shortage of the last period, generates over costs of inventory and maintenance. Consequently, the expression of delay penalties will be given as follows:

$$DP = \sum_{k=1}^{H} C_d \cdot T(k) + \left( C_e \frac{T(H)^2}{2U_{\text{max}}} + C_r(M(2H\tau + T(H)) - M(2H\tau)) \right)$$

where $M(2H\tau + T(H))$ denotes the average number of failures during $[0, (2H\tau + T(H))]$ (the total horizon including the additional interval).

Based on the expression of the average number of failures obtained above, we obtain:

$$M(2H\tau + T(H)) = \sum_{q=1}^{2H} \int_0^\tau \lambda_q(t)dt + \int_{T(H)}^{T(H)} \lambda_{\Delta TA}(t)dt$$

and

$$M(2H\tau) = \sum_{q=1}^{2H} \int_0^\tau \lambda_q(t)dt$$

thus,

$$M = (M(2H\tau + T(H)) - M(2H\tau)) = \int_0^{T(H)} \lambda_{\Delta TA}(t)dt$$

where $\lambda_{\Delta TA}(t)$ denotes the failure rate during the additional interval $\Delta TA$. 

Figure 3. Stock level evolution with delay situation.
The relationship of $\lambda_{\Delta TA}(t)$ with the failure rate during the horizon plan is given by the following expression:

$$\lambda_{\Delta TA}(t) = \lambda_{2H}(\Delta P_b) + \frac{U_{TA}}{U_{\max}} \lambda_{\max}(t).$$

We have: $U(TA) = U_{\max}$. Consequently,

$$\lambda_{\Delta TA}(t) = \lambda_{2H}(\Delta P_b) + \lambda_{\max}(t).$$

On the other hand, we have:

$$\lambda_i(t) = \left[ \frac{i}{2} \right] \lambda_{\max}(t) + \sum_{m=1}^{i} \frac{U(2m-1)}{U_{\max}} \lambda_{\max}(t) \quad (\forall t \in [0, \tau]) \quad (i \geq 1).$$

Thus,

$$\lambda_{2H}(\Delta P_b) = \left[ \frac{2H}{2} \right] \lambda_{\max}(t) + \sum_{m=1}^{2H} \frac{U(2m-1)}{U_{\max}} \lambda_{\max}(t)$$

$$= \left( H + \sum_{m=1}^{2H} \frac{U(2m-1)}{U_{\max}} \right) \lambda_{\max}(t).$$

Finally, the failure rate during the additional interval $\Delta TA$ is expressed as follows:

$$\lambda_{\Delta TA}(t) = \left( H + 1 + \sum_{m=1}^{2H} \frac{U(2m-1)}{U_{\max}} \right) \lambda_{\max}(t).$$

Consequently, the average number of failures during $\Delta TA$ is given by:

$$M = \int_0^{T(H)} \left( H + 1 + \sum_{m=1}^{2H} \frac{U(2m-1)}{U_{\max}} \lambda_{\max}(t) \right) dt$$

$$= \left( H + 1 + \sum_{m=1}^{2H} \frac{U(2m-1)}{U_{\max}} \right) \int_0^{T(H)} \lambda_{\max}(t) dt.$$

Finally,

$$M = \left( H + 1 + \sum_{m=1}^{2H} \frac{U(2m-1)}{U_{\max}} \right) \delta$$

where $\delta = \int_0^{T(H)} \lambda_{\max}(t) dt$.

The expression of delay penalties can be written as follows:

$$DP = \left( \sum_{k=1}^{H} C_d \cdot T(k) \right) + \left( C_h \frac{(T(H))^2}{2U_{\max}} + C_r \left( H + 1 + \sum_{m=1}^{2H} \frac{U(2m-1)}{U_{\max}} \right) \delta \right)$$

(5)

where $\delta = \int_0^{T(H)} \lambda_{\max}(t) dt$. 

3.5 Production revenues

Each product produced by the machine generates unitary revenue depending on the chosen product \((P_a \text{ or } P_b)\). The total revenue is given by the following expression:

\[
PR = PR_a + PR_b
\]

where

\[
PR_a = P_a \sum_{k=1}^{H} d(k)
\]

and

\[
PR_b = P_b \cdot H \cdot (U_{\text{max}} \cdot \Delta P_b).
\]

Consequently,

\[
PR = P_a \sum_{k=1}^{H} d(k) + P_b \cdot H \cdot (U_{\text{max}} \cdot \Delta P_b).
\] (6)

3.6 Total profit

As mentioned above, the total profit of the manufacturing system includes the generated costs (inventory, production, maintenance, and delay penalties) and production revenues generated during the production plan. It is given by the following expression:

\[
TP = PR - (IC + PC + MC + DP).
\]

Based on the expression of each term we obtain:

\[
TP = \left( P_a \sum_{k=1}^{H} d(k) + P_b \cdot H \cdot (U_{\text{max}} \cdot \Delta P_b) \right)
\]

\[
- \left( C_a \sum_{k=1}^{H} \left( \max \left( \sum_{i=1}^{k-1} (U(i) \Delta P_a - d(i)), 0 \right) \Delta t + \frac{1}{2} U(k) \Delta P_a^2 \right) \right)\alpha
\]

\[
- \left( C_p \sum_{k=1}^{H} d(k) + C_b H (U_{\text{max}} \cdot \Delta P_b) \right)\alpha
\]

\[
+ \left( \sum_{k=1}^{H} C_d \cdot T(k) \right) + \left( C_s \frac{T(H)^2}{2U_{\text{max}}} \right) + C_r \left( H + 1 + \sum_{m=1}^{H-2} \left( \frac{U(2m-1)}{U_{\text{max}}} \right) \delta \right)
\] (7)

With \(\alpha = \int_0^\tau \lambda_{\text{max}}(t)dt\) and \(\delta = \int_0^{\tau(H)} \lambda_{\text{max}}(t)dt\).

4. Numerical procedure

Our objective is to determine the optimal production plan, based on the optimal production rate \(U(k)\) of each period \(k (k = 1, \ldots, H)\) and the optimal production interval \(\Delta P_b\) of the secondary product, which maximise the total profit. Solving this problem analytically is too difficult. That is why we choose to solve it with genetic algorithms.

Figure 4 illustrates the main steps of our approach. The ‘reproduction’ step is based on genetic operators to maintain the genetic diversity. Each new population is generated with the standard genetic operators: Multi-point crossover with selection of the best generated chromosomes (80%) and random mutation (5%). Moreover, for each generation, the elite group is maintained (10%) and new random chromosomes are introduced (5%).

Figure 5 illustrates the chromosome structure used in our procedure.

Each gene \(G_i (i = 1, \ldots, H)\) of the first part of chromosome represents the production rate \(U(i)\) during the period \(i\) of the production plan \((i = 1, 2, \ldots, H)\). The second part of the chromosome contains the gene \(G_{H+1}\), which represents the production interval duration of the product \(P_b\).
The following input data were used to illustrate our approach to find the optimal parameters:

- Costs: $C_a = 0.1$/unit/day, $C_b = 2$ $$/unit, $C_c = 4$$$/unit, $C_d = 50$ $$/, $C_r = 25$$, $P_a = 12$$$/unit, $P_r = 8$$$/unit.
- Maximum production rate: $U_{\text{max}} = 30$ units/day.
- Production unit time to failure distribution $F(t)$ when machine produces at the maximum rate $U_{\text{max}}$: Weibull distribution with shape parameter 2 and scale parameter 100. In this case, we have an increasing failure rate $\lambda_{\text{max}}(t) = (2/100)(t/100)$.
- Production plan period duration $\Delta t = 1$ month = 30 days.
- Number of periods (months) $H = 12$.

Figure 6 illustrates the optimal total profit of each generation:

Using this procedure, we obtain the results summarised in the Table 1 after 100 generations:

The optimal duration of production interval of $P_b$ is $\Delta P_{b} = 6.54$ days. The obtained total profit is $TP = 66,628$.

Figures 7 and 8 illustrate the impact of demand on the optimal production rates and the optimal period for $P_b$ production.

In the first case, the manufacturing system must satisfy a high demand: $d(k) = 900$ units $(k = 1, \ldots, H)$. Consequently, the production of $P_b$ is low: $\Delta P_{b} = 0.42$ day.

In the second case, the manufacturing system must satisfy a low demand: $d(k) = 50$ units $(k = 1, \ldots, H)$. Consequently, the production of $P_b$ is high: $\Delta P_{b} = 28.39$ days.

5. Summary and conclusion

In this paper we presented a study of a manufacturing system with a single repairable machine producing two products. We consider dependence between the failure rate and the production rate. The aim is to satisfy a demand at the end of each period. Our objective was to determine the optimal production plan, which includes the production rate during each period and the production duration of each product. A mathematical model and a
Table 1. Optimal production rates.

<table>
<thead>
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<th>Period $k$</th>
<th>$d(k)$</th>
<th>$U(k)^*$</th>
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<tr>
<td>1</td>
<td>800</td>
<td>21,113</td>
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<tr>
<td>2</td>
<td>250</td>
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</table>

Figure 7. Total profit (TP) evolution when demand is high.

Figure 8. Total profit (TP) evolution when demand is low.
genetic optimisation algorithm have been developed in order to determine the optimal plan that maximises the total profit, based on the incurred costs (inventory, production and repairs) and generated revenues by each product.

Improvements of this work are currently under consideration, including the relaxation of the temporal assumptions (production period length, product sequence, etc.)

References


