Maintenance strategy design in a sintering plant based on a multicriteria approach

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Abstract: Maintenance strategy design greatly contributes to ensure the pre-established production capacity of an industrial system and to reduce organisation cost, without compromising customer satisfaction resulting in loss of market share. The focus of the present research is a new model for maintenance policy developed and implemented in a case study. The new approach is focused on the adequate distribution of maintenance budget to system units according to the main factors determining availability and maintenance of equipment. These factors are summarised through appropriate indices, adjusted through a multicriteria method, the analytic hierarchy process (AHP), depending on the importance level of each considered factor and unit of the system. The results can be used as a support for allocation of budgets to maintenance activities, identifying machines or units that are strategic to ensure production. The model has been applied on a real industrial plant.

Keywords: design of maintenance; budgets allocation; failure analysis; analytic hierarchy process; AHP.

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1 Introduction

Maintenance design is a crucial issue consisting of several activities in order to achieve levels of availability and to guarantee the production capacity. The availability of a production system depends on performance and connections of the machines.

For this reason, an industrial plant can be considered as complex system, whose reliability target depends on the performance of its components. In this case the target depends on the quantities set out in the master production schedule and on the service level established in supply contracts (Falcone et al., 2011).

Maintenance design activities are based on information collected by monitoring the condition of machines and processes. Information can be classified into direct information, and indirect information.
For collection of direct information, the parameter fault or wear condition parameters are measured (for example thickness of brake linings). On the other hand, indirect information gives indications on the dynamics of failure, but they are not a direct measure (Christer and Wang, 1995; Raheja et al., 2006).

The literature in this field can be divided into three groups. The first group of research is mainly focused on the determination of effective inspection times, in order to ensure the correct functioning of the machines for predetermined times (Chen and Trivedi, 2002; Wang, 2003; Kalleh and van Noortwijk, 2006; Wang and Jia, 2007).

A common feature of the previous research is that the used information is direct. Consequently, the condition of a system can be verified by monitoring it and then, after an inspection, it is possible to provide appropriate maintenance action. The aim is to determine the best time of inspection, in order to optimise an identified parameter (maximum availability or the minimum cost of production).

A second group of research is focused on the dynamic determination of the inspection time and the time of maintenance or replacement (Castanier et al., 2003; Chen and Trivedi, 2005; Ghasemi et al., 2007; Wang et al., 2009). In this case, future inspections and the maintenance policies are estimated according to specific performance criteria, such as the ‘long-run system availability’ and ‘long-run expected maintenance cost’. For this purpose, information on the wear level of the system result from non-periodic inspections.

The third group of research are intended to determine the optimal level of maintenance or replacement (Banjevic et al., 2001; Chen and Wu, 2007; Lu et al., 2007). A common assumption is that the information collected by monitoring the conditions of the system is indirect. The inspections are carried out periodically and aperiodically but with a predetermined schedule. The aim is to determine a level that optimises a given performance criterion.

Makis and Jardine (1992) give a definition of the limit level of a system, for a random fault. In their model, the checks are carried out at fixed intervals. The equipment is replaced each time it fails. After each inspection and according to the results of the inspection, if the fault cost reaches or exceeds a predetermined limit, a preventive replacement is provided.

The main models in literature assume (often implicitly) an unlimited budget or still adequate to put into practice the actions identified by each method.

This assumption often clashes with the increasing difficulty that companies have to dispose of adequate capital for ideal maintenance policies.

The previous considerations suggest the development of a new approach, able to identify the most relevant criticalities to ensure the production. The basic hypothesis is that a greater strategic importance of the unit or machine must signify greater efforts in terms of maintenance activity.

For this purpose appropriate indices are introduced, to take into account factors that can quantify the importance of each system in a manufacturing process. The proposed method uses the maintenance priority index (MPI) (Silvestri et al., 2014) to quantify the importance of each unit in a manufacturing process, supported by an analytic hierarchy
process (AHP) a well-known technique introduced by Saaty (1980), de Felice and Petrillo (2014) and Grimaldi and Cricelli (2009) that is used to determine how the maintenance of a distributed system may be controlled by appropriately assigning weights to its components.

The paper is organised as follows: Section 2 concerns the AHP, Section 3 introduces the proposed approach to define maintenance priority index (MPI), Section 4 introduces the sintering system and in Section 5 a case study is drawn using the proposed approach. Section 6 is the conclusions.

2 Analytic hierarchy process

The AHP supports decision making by breaking down a problem into several levels in order to form a hierarchy with unidirectional hierarchical relationships between levels. The AHP for decision making uses objective mathematics to process the inescapably subjective and personal preferences of an individual or a group in making a decision. The top level of the hierarchy represents the goal of the problem. The lower levels are the tangible and/or intangible criteria and sub-criteria that contribute to the goal. The bottom level is formed by the alternatives to evaluate in terms of the criteria. Thanks to its generality, the AHP is used in many areas (de Felice and Petrillo, 2014; Grimaldi and Cricelli, 2009). The modelling process can be divided into different phases described as follows:

PHASE 1 Pairwise comparison and relative weight estimation: pairwise comparisons of the elements in each level are conducted with respect to their relative importance towards their control criterion. Saaty suggested a scale of 1–9 when comparing two components (Table 1). For example, number 9 represents extreme importance over another element. And number 8 represents it is between very strong important and extreme importance over another element.

Table 1 Semantics scale of Saaty

<table>
<thead>
<tr>
<th>Intensity of importance $a_{ij}$</th>
<th>Definition</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Equal importance</td>
<td>Two activities contribute equally to the objective</td>
</tr>
<tr>
<td>3</td>
<td>Moderate importance</td>
<td>Experience and judgement slightly favour one activity over another</td>
</tr>
<tr>
<td>5</td>
<td>Strong importance</td>
<td>Experience and judgement strongly favour one activity over another</td>
</tr>
<tr>
<td>7</td>
<td>Very strong or demonstrated importance</td>
<td>An activity is favoured very strongly over another; its dominance demonstrated in practice</td>
</tr>
<tr>
<td>9</td>
<td>Extreme importance</td>
<td>The evidence favouring one activity over another is of the highest possible order of affirmation</td>
</tr>
<tr>
<td>2, 4, 6, 8</td>
<td>For compromise between the above values</td>
<td>Sometimes one needs to interpolate a compromise judgement numerically because there is no good word to describe it</td>
</tr>
</tbody>
</table>
Maintenance strategy design in a sintering plant

For a general AHP application we can consider that \( A_1, A_2, \ldots, A_m \) denote the set of elements, while \( a_{ij} \) represents a quantified judgement on a pair of \( A_i, A_j \). Through the 9-value scale for pairwise comparisons, it yields an \( [m \times m] \) matrix \( A \) as follows:

\[
A = a_{ij} = A_1 \begin{array}{cccc}
1 & a_{12} & \cdots & a_{1m} \\
a_{21} & 1 & \cdots & a_{2m} \\
\vdots & \vdots & \ddots & \vdots \\
a_{m1} & 1/a_{1m} & \cdots & 1
\end{array}
\]

where \( a_{ij} > 0 \) (\( i, j = 1, 2, \ldots, m \)), \( a_{ii} = 1 \) (\( i = 1, 2, \ldots, m \)) and \( a_{ij} = 1/a_{ji} \) (1; 2; \ldots, m). \( A \) is a positive reciprocal matrix.

The result of the comparison is the so-called dominance coefficient \( a_{ij} \) that represents the relative importance of the component on row \( i \) over the component on column \( j \), i.e., \( a_{ij} = w_i/w_j \). The pairwise comparisons can be represented in the form of a matrix. The score of 1 represents equal importance of two components and 9 represents extreme importance of the component \( i \) over the component \( j \).

In matrix \( A \), the problem becomes one of assigning to the \( m \) elements \( A_1, A_2, \ldots, A_m \) a set of numerical weights \( w_1, w_2, \ldots, w_m \) that reflects the recorded judgements. If \( A \) is a consistency matrix, the relations between weights \( w_i, w_j \) and judgements \( a_{ij} \) are simply given by \( a_{ij} = w_i/w_j \) (for \( i, j = 1, 2, \ldots, m \)) and

\[
A = \begin{array}{cccc}
w_1/w_1 & w_1/w_2 & \cdots & w_1/w_m \\
w_2/w_1 & w_2/w_2 & \cdots & w_2/w_m \\
\vdots & \vdots & \ddots & \vdots \\
w_m/w_1 & w_m/w_2 & \cdots & w_m/w_m
\end{array}
\]

If matrix \( w \) is a non-zero vector, there is a \( \lambda_{\text{max}} \) of \( Aw = \lambda_{\text{max}}w \), which is the largest eigenvalue of matrix \( A \). If matrix \( A \) is perfectly consistent, then \( \lambda_{\text{max}}w = m \). But given that \( a_{ij} \) denotes the subjective judgement of decision makers, who give comparison and appraisal, with the actual value (\( w_i/w_j \)) having a certain degree of variation. Therefore, \( Ax = \lambda_{\text{max}}w \) cannot be set up. So the judgement matrix of the traditional AHP always needs to be revised for its consistency.

**PHASE 2**  
*Priority vector:* after all pairwise comparison is completed, the priority weight vector \( (w) \) is computed as the unique solution of \( Aw = \lambda_{\text{max}}w \), where \( \lambda_{\text{max}} \) is the largest eigenvalue of matrix \( A \).

**PHASE 3**  
*Consistency index estimation:* Saaty (1980) proposed utilising consistency index (CI) to verify the consistency of the comparison matrix. The consistency index (CI) of the derived weights could then be calculated by:

\[ CI = (\lambda_{\text{max}} - n)/n - 1 \]

In general, if CI is less than 0.10, satisfaction of judgements may be derived.
3 Maintenance critical analysis-based AHP

The introduced methodology, called maintenance critical analysis (MCA), aims to identify units or machines that have the most critical maintenance and require major investments.

The method is structured in the following steps (Zaim et al., 2012):

Step 1 Plant breakdown: it is necessary preliminary to define what are the units or machines that break down the system to be analysed. At this stage of breaking down, some basic rules must be observed:

- the number of components has to be such as to adequately describe the specifics of the system, however, does not create problems of data management, due to a too detailed breakdown
- for chosen parts, the parameters used for the analysis must be uniquely and easily identified.

Step 2 Data collection: for the selected units, the data needed to calculate the indicators $A_1, A_2, A_3, A_4, A_5, A_6$, for MCA where:

\[
\text{FlowIndex}_{i} (A_i) = \frac{F_i}{F_{tot}}
\]

This technical indicator is intended as a measure of the importance that the unit or the machine covers in the production process. $F_i$ is flow of materials in the machine $i^{th}$ and $F_{tot}$ is flow of materials in the system.

It always takes positive values between 0 and 1; in particular take values close to one, in case of indispensable units for production.

The flow index takes into account, even if indirectly, the production process and the functional connections between the machines.

For companies with a single product line layout (Figure 1), the flow rate will be the same for each machine with value always equal to 1, $F_1 = F_2 = \ldots = F_n = 1$ (unless bypass along the process).

**Figure 1** Line layout flow

![Line layout flow](image)

In case of more complex layout configurations, with more production lines or machines in parallel, the flow index can be calculated as in the example shown in Figure 2.

Being $F_i$ the flow of materials in the machine $i^{th}$, and assuming that the takt times are equal, is possible to assume values of flow as follows:
Maintenance strategy design in a sintering plant

\[ F_1 = F_3 = F_{\text{tot}} \]
\[ F_7 = \text{output flow material of the system} \]
\[ F_2 + F_3 = F_1 \] (input flow material is divided into M2 and M3)
\[ F_1 = 2F_2 \] (so \( F_2 = \frac{1}{3}F_1 \) and \( F_3 = \frac{2}{3}F_1 \))
\[ F_4 = F_5 \quad \text{and} \quad F_4 + F_5 = F_2 \]
\[ F_2 = F_6 = F_4 + F_5 \]

Figure 2 Example of complex layout (parallel configuration)

It will result for example, the following values of the flow index:

\[ A_1 = F_1 / F_{\text{tot}} = 1 \]
\[ A_2 = F_2 / F_{\text{tot}} = \frac{1}{3} \]
\[ A_3 = F_3 / F_{\text{tot}} = \frac{2}{3} \]
\[ A_4 = F_4 / F_{\text{tot}} = \frac{1}{6} \]
\[ A_5 = F_5 / F_{\text{tot}} = A_4 = \frac{1}{6} \]
\[ A_6 = F_6 / F_{\text{tot}} = A_2 = \frac{1}{3} \]
\[ A_7 = F_7 / F_{\text{tot}} = A_1 = 1 \]

In calculating the index, it is necessary to measure the flow of materials in a way suited to the specific production process (number of pieces, weight, capacity, MAG).

\[
\text{TimeIndex}_{ij}(A_2) = \frac{\sum_{j=1}^{n} T_{ij}}{\sum_{i=1}^{n} \left( \sum_{j=1}^{n} TC_i \right)} \quad (2)
\]

\(
\text{TimeIndex}(A_2) \) for the unit or machine \( \rho \text{th} \) is the ratio between the working time of the machine for a unit of product \( \sum_{j=1}^{n} T_{ij} \) and the takt time of the product \( \left( \sum_{j=1}^{n} TC_i \right) \).
In case of multi-product company, where the same machine is used for the production of different products, the index formula is different.

\( P_1 \ldots P_n \) are the products made by the company. If we denote \( TC_1 \ldots TC_n \) as the takt times for each product and \( T_{ij} \) as the time in which the \( i^{th} \) machine works the product \( j \).

\[
\text{MaintenanceIndex} \left( A_3 \right) = \frac{T_{mi}}{T_{m\text{tot}}} \tag{3}
\]

\( \text{MaintenanceIndex}(A_3) \) is given by the ratio between the average number of hours spent in maintenance in the \( i^{th} \) station \( (T_{mi}) \) and the average number of hours of maintenance time, calculated for the unit with the highest maintenance time \( (T_{m\text{max}}) \). The introduced index can take only positive values up to 1, in the case of a unit with the highest maintenance time.

\[
\text{CostIndex} \left( A_4 \right) = \frac{C_{mi}}{C_{m\text{tot}}} \tag{4}
\]

\( \text{CostIndex}(A_4) \) is the ratio between the annual cost of maintenance for the \( i^{th} \) unit \( (C_{mi}) \) and total cost of maintenance of the system \( (C_{m\text{tot}}) \) in a year. Differently from the previous, it is a purely economic indicator, to estimate the importance of the unit in terms of cost in maintenance.

Also in this case the index takes values greater than 0 and can be 1 if the entire cost of maintenance of the company is used for the analysed unit. The index only takes into account the costs for industrial maintenance.

\[
\text{FailureModeIndex} \left( A_5 \right) = \frac{F_{mi}}{F_{m\text{tot}}} \tag{5}
\]

\( \text{FailureModeIndex}(A_5) \) is the ratio between the failure modes occurring in the \( i^{th} \) machine \( (F_{mi}) \) and all the different failure modes \( (F_{m\text{tot}}) \) of the plant (in a year). The term ‘failure mode’ refers to the diversity of faults and not to their number.

\[
\text{FailureNumberIndex} \left( A_6 \right) = \frac{F_{ni}}{F_{n\text{tot}}} \tag{6}
\]

\( \text{FailureNumberIndex}(A_6) \) is the ratio between the failure numbers occurring in the \( i^{th} \) machine \( (F_{ni}) \) and all failure numbers \( (F_{n\text{tot}}) \) of the plant (in a year).

This operation may require, in some cases, an extended period of time.

### Step 3  Definition of the indicators matrix \([1 \times 6]\)

<table>
<thead>
<tr>
<th>( A_1 )</th>
<th>( A_2 )</th>
<th>( A_3 )</th>
<th>( A_4 )</th>
<th>( A_5 )</th>
<th>( A_6 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit 1</td>
<td>( w_1 = \frac{F_i}{F_{n\text{tot}}} )</td>
<td>( w_2 = \frac{\sum_{j=1}^{n} T_{ij}}{\sum_{j=1}^{n} \sum_{i=1}^{n} TC_j} )</td>
<td>( w_3 = \frac{T_{m1}}{T_{m\text{tot}}} )</td>
<td>( w_4 = \frac{C_{m1}}{C_{m\text{tot}}} )</td>
<td>( w_5 = \frac{F_{m1}}{F_{m\text{tot}}} )</td>
</tr>
</tbody>
</table>
Maintenance strategy design in a sintering plant

Unit 2
\[ w_{21} = \frac{F_2}{F_{tot}} \quad w_{22} = \frac{\sum_{j=1}^{n} T_{2j}}{\sum_{j=1}^{n} \sum_{i=1}^{n} T_{ij}} \quad w_{23} = \frac{T_{m2}}{T_{m_{tot}}} \quad w_{24} = \frac{C_{m2}}{C_{m_{tot}}} \quad w_{25} = \frac{F_{m2}}{F_{m_{tot}}} \quad w_{26} = \frac{F_{n2}}{F_{n_{tot}}} \]

Unit 3
\[ w_{31} = \frac{F_3}{F_{tot}} \quad w_{32} = \frac{\sum_{j=1}^{n} T_{3j}}{\sum_{j=1}^{n} \sum_{i=1}^{n} T_{ij}} \quad w_{33} = \frac{T_{m3}}{T_{m_{tot}}} \quad w_{34} = \frac{C_{m3}}{C_{m_{tot}}} \quad w_{35} = \frac{F_{m3}}{F_{m_{tot}}} \quad w_{36} = \frac{F_{n3}}{F_{n_{tot}}} \]

... ... ... ... ... ...

Unit i
\[ w_{i1} = \frac{F_i}{F_{tot}} \quad w_{i2} = \frac{\sum_{j=1}^{n} T_{ij}}{\sum_{j=1}^{n} \sum_{i=1}^{n} T_{ij}} \quad w_{i3} = \frac{T_{m_i}}{T_{m_{tot}}} \quad w_{i4} = \frac{C_{m_i}}{C_{m_{tot}}} \quad w_{i5} = \frac{F_{m_i}}{F_{m_{tot}}} \quad w_{i6} = \frac{F_{n_i}}{F_{n_{tot}}} \]

Step 4 According to Saaty’s scale, AHP method is applied to system units, as show in the following AHP unit matrix (pairwise comparison between units).

<table>
<thead>
<tr>
<th>Unit 1</th>
<th>Unit 2</th>
<th>Unit 3</th>
<th>Unit 4</th>
<th>Unit 5</th>
<th>Unit 6</th>
<th>Unit 7</th>
<th>Unit 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit 1</td>
<td>( w_{11} \times w_{12} )</td>
<td>( w_{11} \times w_{13} )</td>
<td>( w_{11} \times w_{14} )</td>
<td>( w_{11} \times w_{15} )</td>
<td>( w_{11} \times w_{16} )</td>
<td>( w_{11} \times w_{17} )</td>
<td>( w_{11} \times w_{18} )</td>
</tr>
<tr>
<td>Unit 2</td>
<td>( w_{21} \times w_{22} )</td>
<td>( w_{22} \times w_{23} )</td>
<td>( w_{22} \times w_{24} )</td>
<td>( w_{22} \times w_{25} )</td>
<td>( w_{22} \times w_{26} )</td>
<td>( w_{22} \times w_{27} )</td>
<td>( w_{22} \times w_{28} )</td>
</tr>
<tr>
<td>Unit 3</td>
<td>( w_{31} \times w_{32} )</td>
<td>( w_{32} \times w_{33} )</td>
<td>( w_{32} \times w_{34} )</td>
<td>( w_{32} \times w_{35} )</td>
<td>( w_{32} \times w_{36} )</td>
<td>( w_{32} \times w_{37} )</td>
<td>( w_{32} \times w_{38} )</td>
</tr>
<tr>
<td>Unit 4</td>
<td>( w_{41} \times w_{42} )</td>
<td>( w_{42} \times w_{43} )</td>
<td>( w_{42} \times w_{44} )</td>
<td>( w_{42} \times w_{45} )</td>
<td>( w_{42} \times w_{46} )</td>
<td>( w_{42} \times w_{47} )</td>
<td>( w_{42} \times w_{48} )</td>
</tr>
<tr>
<td>Unit 5</td>
<td>( w_{51} \times w_{52} )</td>
<td>( w_{52} \times w_{53} )</td>
<td>( w_{52} \times w_{54} )</td>
<td>( w_{52} \times w_{55} )</td>
<td>( w_{52} \times w_{56} )</td>
<td>( w_{52} \times w_{57} )</td>
<td>( w_{52} \times w_{58} )</td>
</tr>
<tr>
<td>Unit 6</td>
<td>( w_{61} \times w_{62} )</td>
<td>( w_{62} \times w_{63} )</td>
<td>( w_{62} \times w_{64} )</td>
<td>( w_{62} \times w_{65} )</td>
<td>( w_{62} \times w_{66} )</td>
<td>( w_{62} \times w_{67} )</td>
<td>( w_{62} \times w_{68} )</td>
</tr>
<tr>
<td>Unit 7</td>
<td>( w_{71} \times w_{72} )</td>
<td>( w_{72} \times w_{73} )</td>
<td>( w_{72} \times w_{74} )</td>
<td>( w_{72} \times w_{75} )</td>
<td>( w_{72} \times w_{76} )</td>
<td>( w_{72} \times w_{77} )</td>
<td>( w_{72} \times w_{78} )</td>
</tr>
<tr>
<td>Unit 8</td>
<td>( w_{81} \times w_{82} )</td>
<td>( w_{82} \times w_{83} )</td>
<td>( w_{82} \times w_{84} )</td>
<td>( w_{82} \times w_{85} )</td>
<td>( w_{82} \times w_{86} )</td>
<td>( w_{82} \times w_{87} )</td>
<td>( w_{82} \times w_{88} )</td>
</tr>
</tbody>
</table>

The result is a ranking vector for units \([i\times1]\), as follows:

\[
\begin{align*}
\text{Unit 1} & : z_{11} \\
\text{Unit 2} & : z_{21} \\
\text{Unit 3} & : z_{31} \\
\vdots & : \\
\text{Unit i} & : z_{i1}
\end{align*}
\]

where \( \sum_{i=1}^{n} z_{ij} = 1 \), and the unit with \( z_{1\text{max}} \) it will be the unit with a lower value of performance for maintenance budget allocation process.

Then, according to Saaty’s scale, a pairwise comparison among factors \( A_1, A_2, A_3, A_4, A_5, A_6 \) will be defined as show in the following AHP factor matrix \([6\times6]\):
The result is a ranking vector for factors $[1 \times 6]$, as follows:

\[
\begin{align*}
  A_1 & & A_2 & & A_3 & & A_4 & & A_5 & & A_6 \\
  y_1/y_1 & & y_1/y_2 & & y_1/y_3 & & \ldots & & \ldots & & y_1/y_6 \\
  y_2/y_1 & & \ldots & & \ldots & & \ldots & & \ldots & & \ldots \\
  y_3/y_1 & & \ldots & & \ldots & & \ldots & & \ldots & & \ldots \\
  \ldots & & \ldots & & \ldots & & \ldots & & \ldots & & \ldots \\
  \ldots & & \ldots & & \ldots & & \ldots & & \ldots & & \ldots \\
  y_6/y_1 & & \ldots & & \ldots & & \ldots & & \ldots & & y_6/y_6
\end{align*}
\]

where $\sum_{i=1}^{6} h_{ij} = 1$ and $A_i$ with $h_{i\text{max}}$ will be decisive in the maintenance budget allocation process.

Finally, in the present step there will be the definition of AHP weights matrix $[i \times 6]$ obtained by multiplying the units vector ranking ($z_{ij}$) with the factors vector ranking ($h_{ij}$).

$k_{ij} = z_{ij} \times h_{ij}$ represent the importance of the $i^{th}$ unit regard to $A_i$. Furthermore, it is important to note that:

- The sum of $i^{th}$ row is equal to $\sum_{j=1}^{6} K_{ij} = z_{i1}$ (weight of the $i^{th}$ unit distributed among the factors $A_i$).

- The sum of $j^{th}$ column is equal to $\sum_{i=1}^{n} K_{ij} = h_{1j}$ (weight of factors $A_i$ distributed among units).

Consequently the sum is $\sum_{j=1}^{n} \sum_{i=1}^{6} K_{ij} = 1$, as shown in the following AHP weighs matrix:

\[
\begin{align*}
  & A_1 & A_2 & A_3 & A_4 & A_5 & A_6 & \sum_{j=1}^{6} K_{ij} \\
  \text{Unit 1} & k_{11} & k_{12} & k_{13} & k_{14} & k_{15} & k_{16} & z_{11} \\
  & k_{21} & k_{22} & k_{23} & k_{24} & k_{25} & k_{26} & z_{21} \\
  & k_{31} & k_{32} & k_{33} & k_{34} & k_{35} & k_{36} & z_{31} \\
  & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
  \text{Unit } i & k_{i1} & k_{i2} & k_{i3} & k_{i4} & k_{i5} & k_{i6} & z_{i1} \\
  \sum_{i=1}^{n} K_{1i} & h_{11} & h_{12} & h_{13} & h_{14} & h_{15} & h_{16} & \sum_{i=1}^{n} \sum_{j=1}^{6} K_{ij} = 1
\end{align*}
\]

The $k_{ij}$ values are the AHP weights for $A_i$ indicators.
Step 5  Definition of MPA matrix (Bevilacqua and Braglia, 2000) obtained by multiplying each other the values $w_i$ of the indicators matrix (Step 3) and the values $k_{ij}$ AHP weights matrix (Step 4), where $P_{ij} = k_{ij} \times w_i$

$$
\begin{array}{|c|c|c|c|c|c|}
\hline
& A_1 & A_2 & A_3 & A_4 & A_5 & A_6 \\
\hline
\text{Unit 1} & P_{11} & P_{12} & P_{13} & P_{14} & P_{15} & P_{16} \\
\text{Unit 2} & P_{21} & P_{22} & P_{23} & P_{24} & P_{25} & P_{26} \\
\text{Unit 3} & P_{31} & P_{32} & P_{33} & P_{34} & P_{35} & P_{36} \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
\text{Unit i} & P_{i1} & P_{i2} & P_{i3} & P_{i4} & P_{i5} & P_{i6} \\
\hline
\end{array}
$$

Step 6  The calculated parameters ($P_{ij}$) for each unit, are summarised in a single index (Cai et al., 2016), called the maintenance priority index (MPI) calculated for each machine. The mathematical formulation of MPI is as follows:

$$
MPI_i = P_{i1} \times P_{i2} \times P_{i3} \times P_{i4} \times P_{i5} \times P_{i6}
$$

Then we calculated the $MPI_i$ percentile, as follows:

$$
MPI_i,\% = \frac{MPI_i}{\sum_{i=1}^{n} MPI_i} \times 100
$$

The introduced index can take values between 0 and 1, directly proportional to the criticality related to the unit or the machine.

Step 7  Analysis of results: by ordering the units according to a decreasing value of MPI, the list of maintenance priorities is obtained.

According to these priorities, maintenance must be designed and budgets must be allocated.

Units with higher values of MPI require more resources used in maintenance activities. Their unavailability may in fact seriously undermine the success of the production process.

4 The production process and the sintering products

Powders metallurgy technology, to produce finished metal or metal ceramic pieces, starting from powders mixed through pressing and sintering operations.

The raw materials are metal carbides, usually tungsten carbide and cobalt powders.

Before being compacted, the powders are mixed in spherical mills, by adding well-defined quantities of solid lubricant (paraffin) and a solvent (isopropyl alcohol). Alcohol is used to help the uniform distribution of the mass of the powders, forming a fluid mixture. After the removal of the solvent, the paraffin covers the particles of powder and helps their union and compacting on the following phase of pressing or extrusion. The retrieval of the used solvent is obtained through a mixture drying process under vacuum.
The next step to drying is pressing, which can be done in two different ways:

- **mechanical**: production of pieces in a finished shape and of small-medium size
- **hydraulic**: production of box-shaped pieces and of medium-big size.

**Figure 3** Functional diagram of the productive cycle

The extrusion process enables, as well as the hydraulic pressing, to obtain box-shaped and very long pieces. The products obtained are then de-lubricated and pre-sintered, in order to give suitable capacities of mechanical resistance for the following moulding process. The obtained product is sent to the sintering phase. The cycle is carried out in induction or resistance furnaces; and aims to change the powder mixtures into a solid body (Figure 3).

The fundamental parameters of such process are:

- time
- temperature
- shape and sizes of the particles
- surface state of the particles
- degree of compacting.

The productive cycle is shown schematically in Figure 3.
5 MCA application to sintering system

The proposed approach was applied to a Sintering System described in Section 4:

Step 1 Plant Breakdown: starting from Figure 1, the Product Tree and the Reliability Block Diagram (series configuration) have pointed out these units:
- Unit 1 mixer
- Unit 2 dryer
- Unit 3 extruder
- Unit 4 mechanical press
- Unit 5 hydraulic press
- Unit 6 de-lubricator
- Unit 7 moulding
- Unit 8 sintering.

Step 2 Starting from data collection of Sintering System (from 2014 to 2016), indicators $A_1$, $A_2$, $A_3$, $A_4$, $A_5$, $A_6$, for each units are evaluated.

Applying equation (1), we obtained (Table 2):

Table 2  Flow index values

<table>
<thead>
<tr>
<th>Unit</th>
<th>$A_{F_i}$ (Mag)</th>
<th>$A_{F_{tot}}$ (Mag)</th>
<th>$A_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit 1</td>
<td>780</td>
<td>780</td>
<td>1</td>
</tr>
<tr>
<td>Unit 2</td>
<td>780</td>
<td>780</td>
<td>1</td>
</tr>
<tr>
<td>Unit 3</td>
<td>365</td>
<td>780</td>
<td>0.47</td>
</tr>
<tr>
<td>Unit 4</td>
<td>182.5</td>
<td>780</td>
<td>0.23</td>
</tr>
<tr>
<td>Unit 5</td>
<td>182.5</td>
<td>780</td>
<td>0.23</td>
</tr>
<tr>
<td>Unit 6</td>
<td>548</td>
<td>780</td>
<td>0.70</td>
</tr>
<tr>
<td>Unit 7</td>
<td>548</td>
<td>780</td>
<td>0.70</td>
</tr>
<tr>
<td>Unit 8</td>
<td>780</td>
<td>780</td>
<td>1</td>
</tr>
</tbody>
</table>

Applying equation (2), we obtained Table 3.

Table 3  Time index values

<table>
<thead>
<tr>
<th>Unit</th>
<th>$A_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit 1</td>
<td>0.05</td>
</tr>
<tr>
<td>Unit 2</td>
<td>0.05</td>
</tr>
<tr>
<td>Unit 3</td>
<td>0.05</td>
</tr>
<tr>
<td>Unit 4</td>
<td>0.15</td>
</tr>
<tr>
<td>Unit 5</td>
<td>0.15</td>
</tr>
<tr>
<td>Unit 6</td>
<td>0.05</td>
</tr>
<tr>
<td>Unit 7</td>
<td>0.25</td>
</tr>
<tr>
<td>Unit 8</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Applying equation (3), we obtained Table 4.

Table 4  Maintenance Index values

<table>
<thead>
<tr>
<th>Unit</th>
<th>$T_{mi}$ (h)</th>
<th>$T_{m_{max}}$ (h)</th>
<th>$A_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit 1</td>
<td>29.3</td>
<td>293</td>
<td>0.1</td>
</tr>
<tr>
<td>Unit 2</td>
<td>58.6</td>
<td>293</td>
<td>0.2</td>
</tr>
<tr>
<td>Unit 3</td>
<td>29.3</td>
<td>293</td>
<td>0.1</td>
</tr>
<tr>
<td>Unit 4</td>
<td>210.96</td>
<td>293</td>
<td>0.72</td>
</tr>
<tr>
<td>Unit 5</td>
<td>216.82</td>
<td>293</td>
<td>0.74</td>
</tr>
<tr>
<td>Unit 6</td>
<td>234.4</td>
<td>293</td>
<td>0.8</td>
</tr>
<tr>
<td>Unit 7</td>
<td>234.4</td>
<td>293</td>
<td>0.8</td>
</tr>
<tr>
<td>Unit 8</td>
<td>293</td>
<td>293</td>
<td>1</td>
</tr>
</tbody>
</table>
Applying equation (4), we obtained Table 5.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Unit 2</th>
<th>Unit 3</th>
<th>Unit 4</th>
<th>Unit 5</th>
<th>Unit 6</th>
<th>Unit 7</th>
<th>Unit 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cm_i (€)</td>
<td>7,560</td>
<td>34,020</td>
<td>24,570</td>
<td>24,570</td>
<td>20,790</td>
<td>22,680</td>
<td>26460</td>
</tr>
<tr>
<td>Cm tot (€)</td>
<td>189,000</td>
<td>189,000</td>
<td>189,000</td>
<td>189,000</td>
<td>189,000</td>
<td>189,000</td>
<td>189,000</td>
</tr>
<tr>
<td>A_4</td>
<td>0.04</td>
<td>0.18</td>
<td>0.13</td>
<td>0.13</td>
<td>0.11</td>
<td>0.12</td>
<td>0.14</td>
</tr>
</tbody>
</table>

Applying equation (5), we obtained Table 6.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Unit 2</th>
<th>Unit 3</th>
<th>Unit 4</th>
<th>Unit 5</th>
<th>Unit 6</th>
<th>Unit 7</th>
<th>Unit 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fm_i</td>
<td>2</td>
<td>8.5</td>
<td>5</td>
<td>8</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Fm tot</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>A_5</td>
<td>0.04</td>
<td>0.17</td>
<td>0.1</td>
<td>0.16</td>
<td>0.12</td>
<td>0.12</td>
<td>0.12</td>
</tr>
</tbody>
</table>

Applying equation (6), we obtained Table 7.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Unit 2</th>
<th>Unit 3</th>
<th>Unit 4</th>
<th>Unit 5</th>
<th>Unit 6</th>
<th>Unit 7</th>
<th>Unit 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fn_i</td>
<td>1</td>
<td>59</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>10</td>
<td>13</td>
</tr>
<tr>
<td>Fn tot</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>A_6</td>
<td>0.01</td>
<td>0.59</td>
<td>0.01</td>
<td>0.02</td>
<td>0.01</td>
<td>0.10</td>
<td>0.13</td>
</tr>
</tbody>
</table>

Step 3  Definition MPA matrix [8×6]:

<table>
<thead>
<tr>
<th>Unit</th>
<th>A_1</th>
<th>A_2</th>
<th>A_3</th>
<th>A_4</th>
<th>A_5</th>
<th>A_6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit 1</td>
<td>1.00</td>
<td>0.05</td>
<td>0.10</td>
<td>0.04</td>
<td>0.04</td>
<td>0.01</td>
</tr>
<tr>
<td>Unit 2</td>
<td>1.00</td>
<td>0.05</td>
<td>0.20</td>
<td>0.18</td>
<td>0.17</td>
<td>0.59</td>
</tr>
<tr>
<td>Unit 3</td>
<td>0.47</td>
<td>0.05</td>
<td>0.10</td>
<td>0.13</td>
<td>0.10</td>
<td>0.01</td>
</tr>
<tr>
<td>Unit 4</td>
<td>0.23</td>
<td>0.15</td>
<td>0.72</td>
<td>0.13</td>
<td>0.16</td>
<td>0.02</td>
</tr>
<tr>
<td>Unit 5</td>
<td>0.23</td>
<td>0.15</td>
<td>0.74</td>
<td>0.11</td>
<td>0.12</td>
<td>0.01</td>
</tr>
<tr>
<td>Unit 6</td>
<td>0.70</td>
<td>0.05</td>
<td>0.80</td>
<td>0.12</td>
<td>0.12</td>
<td>0.10</td>
</tr>
<tr>
<td>Unit 7</td>
<td>0.70</td>
<td>0.25</td>
<td>0.80</td>
<td>0.14</td>
<td>0.12</td>
<td>0.13</td>
</tr>
<tr>
<td>Unit 8</td>
<td>1.00</td>
<td>0.25</td>
<td>1.00</td>
<td>0.15</td>
<td>0.17</td>
<td>0.13</td>
</tr>
</tbody>
</table>

Step 4  AHP method applied to units and to factors (Jablonsky, 2015): through Saaty’s scale pairwise comparisons (Tsyganok et al., 2015) between units were obtained, as shows in the following AHP matrix for units:

<table>
<thead>
<tr>
<th>Unit</th>
<th>Unit 2</th>
<th>Unit 3</th>
<th>Unit 4</th>
<th>Unit 5</th>
<th>Unit 6</th>
<th>Unit 7</th>
<th>Unit 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit 1</td>
<td>1.000</td>
<td>3.000</td>
<td>1.000</td>
<td>9.000</td>
<td>3.000</td>
<td>9.000</td>
<td>7.000</td>
</tr>
<tr>
<td>Unit 2</td>
<td>0.333</td>
<td>1.000</td>
<td>0.333</td>
<td>4.000</td>
<td>1.000</td>
<td>6.000</td>
<td>3.000</td>
</tr>
<tr>
<td>Unit 3</td>
<td>1.000</td>
<td>3.000</td>
<td>1.000</td>
<td>9.000</td>
<td>3.000</td>
<td>9.000</td>
<td>7.000</td>
</tr>
<tr>
<td>Unit 4</td>
<td>0.111</td>
<td>0.250</td>
<td>0.111</td>
<td>1.000</td>
<td>0.250</td>
<td>1.000</td>
<td>1.000</td>
</tr>
</tbody>
</table>
Maintenance strategy design in a sintering plant

<table>
<thead>
<tr>
<th>Unit</th>
<th>0.333</th>
<th>1.000</th>
<th>0.333</th>
<th>4.000</th>
<th>1.000</th>
<th>6.000</th>
<th>3.000</th>
<th>1.000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit 5</td>
<td>0.111</td>
<td>0.167</td>
<td>0.111</td>
<td>1.000</td>
<td>0.167</td>
<td>1.000</td>
<td>0.500</td>
<td>0.250</td>
</tr>
<tr>
<td>Unit 6</td>
<td>0.143</td>
<td>0.333</td>
<td>0.143</td>
<td>1.000</td>
<td>0.333</td>
<td>2.000</td>
<td>1.000</td>
<td>0.500</td>
</tr>
<tr>
<td>Unit 7</td>
<td>0.250</td>
<td>1.000</td>
<td>0.250</td>
<td>3.000</td>
<td>1.000</td>
<td>4.000</td>
<td>2.000</td>
<td>1.000</td>
</tr>
</tbody>
</table>

The final ranking vector for units is the following:

<table>
<thead>
<tr>
<th>Unit</th>
<th>0.3149</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit 2</td>
<td>0.1084</td>
</tr>
<tr>
<td>Unit 3</td>
<td>0.3040</td>
</tr>
<tr>
<td>Unit 4</td>
<td>0.0283</td>
</tr>
<tr>
<td>Unit 5</td>
<td>0.1084</td>
</tr>
<tr>
<td>Unit 6</td>
<td>0.0193</td>
</tr>
<tr>
<td>Unit 7</td>
<td>0.0424</td>
</tr>
<tr>
<td>Unit 8</td>
<td>0.0745</td>
</tr>
</tbody>
</table>

Results show for the unit 1 the lower reliability allocated.

According to Saaty’s scale it will be defined a pairwise comparison among factors $A_1$, $A_2$, $A_3$, $A_4$, $A_5$, $A_6$. The result is an AHP matrix for factors $[6 \times 6]$, as follows:

<table>
<thead>
<tr>
<th>$A_1$</th>
<th>$A_2$</th>
<th>$A_3$</th>
<th>$A_4$</th>
<th>$A_5$</th>
<th>$A_6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_1$</td>
<td>1.000</td>
<td>0.333</td>
<td>0.333</td>
<td>0.167</td>
<td>0.111</td>
</tr>
<tr>
<td>$A_2$</td>
<td>3.000</td>
<td>1.000</td>
<td>1.000</td>
<td>0.500</td>
<td>0.200</td>
</tr>
<tr>
<td>$A_3$</td>
<td>3.000</td>
<td>1.000</td>
<td>1.000</td>
<td>0.500</td>
<td>0.200</td>
</tr>
<tr>
<td>$A_4$</td>
<td>6.000</td>
<td>2.000</td>
<td>2.000</td>
<td>1.000</td>
<td>0.500</td>
</tr>
<tr>
<td>$A_5$</td>
<td>9.000</td>
<td>5.000</td>
<td>5.000</td>
<td>2.000</td>
<td>1.000</td>
</tr>
<tr>
<td>$A_6$</td>
<td>9.000</td>
<td>5.000</td>
<td>5.000</td>
<td>2.000</td>
<td>1.000</td>
</tr>
</tbody>
</table>

The final ranking vector for factors is the following:

<table>
<thead>
<tr>
<th>$A_1$</th>
<th>$A_2$</th>
<th>$A_3$</th>
<th>$A_4$</th>
<th>$A_5$</th>
<th>$A_6$</th>
<th>$\sum_{i=1}^{6} z_{i}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0388</td>
<td>0.1073</td>
<td>0.1055</td>
<td>0.2381</td>
<td>0.4846</td>
<td>0.0258</td>
<td>1.0000</td>
</tr>
</tbody>
</table>

AHP weight matrix $[8 \times 6]$ obtained by multiplying the two final vectors (units and factors) is the following:

<table>
<thead>
<tr>
<th>$A_1$</th>
<th>$A_2$</th>
<th>$A_3$</th>
<th>$A_4$</th>
<th>$A_5$</th>
<th>$A_6$</th>
<th>$\sum_{j=1}^{6} K_{ij} = z_{i1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit 1</td>
<td>0.0122</td>
<td>0.0338</td>
<td>0.0332</td>
<td>0.0750</td>
<td>0.1526</td>
<td>0.0081</td>
</tr>
</tbody>
</table>
Step 5 Multiplying MPA matrix and AHP weight matrix the result is the MPA-AHP matrix.

\[
\sum_{i=1}^{n} K_{ij} = h_i
\]

\[
\begin{array}{ccccccccc}
0.0388 & 0.1073 & 0.1055 & 0.2381 & 0.4846 & 0.0258 \\
\end{array}
\]

\[
\sum_{j=1}^{n} \sum_{i=1}^{n} K_{ij} = 1
\]

Step 6 Applying equation (7), we obtained:

\[
\begin{array}{cccccc}
A1 & A2 & A3 & A4 & A5 & A6 \\
\end{array}
\]

\[
\begin{array}{cccccc}
0.0122 & 0.00169 & 0.00332 & 0.003 & 0.006104 & 0.000081 \\
0.0042 & 0.00058 & 0.00228 & 0.004644 & 0.008925 & 0.001652 \\
0.005546 & 0.00163 & 0.00321 & 0.009412 & 0.01473 & 0.00078 \\
0.000253 & 0.00045 & 0.00216 & 0.000871 & 0.002192 & 0.00014 \\
0.000966 & 0.00174 & 0.008436 & 0.002838 & 0.0063 & 0.00028 \\
0.00049 & 0.000105 & 0.0016 & 0.000552 & 0.001128 & 0.00005 \\
0.00112 & 0.001125 & 0.0036 & 0.001414 & 0.00246 & 0.000143 \\
0.0029 & 0.002 & 0.0079 & 0.002655 & 0.006137 & 0.000247 \\
\end{array}
\]

Applying equation (8), we obtained Table 8.

<table>
<thead>
<tr>
<th>Unit 1</th>
<th>Unit 2</th>
<th>Unit 3</th>
<th>Unit 4</th>
<th>Unit 5</th>
<th>Unit 6</th>
<th>Unit 7</th>
<th>Unit 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPI%</td>
<td>10.26%</td>
<td>38.44%</td>
<td>31.72%</td>
<td>0.00%</td>
<td>0.72%</td>
<td>0.00%</td>
<td>0.23%</td>
</tr>
</tbody>
</table>

Step 7 Analysis of results: the units ranking based on MPI% is shown in Table 9.
Table 9  Unit ranking

<table>
<thead>
<tr>
<th>Ranking</th>
<th>Unit</th>
<th>MPI%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>dryer</td>
<td>38.44%</td>
</tr>
<tr>
<td>2</td>
<td>extruder</td>
<td>31.72%</td>
</tr>
<tr>
<td>3</td>
<td>sintering</td>
<td>18.64%</td>
</tr>
<tr>
<td>4</td>
<td>mixer</td>
<td>10.26%</td>
</tr>
<tr>
<td>5</td>
<td>hydraulic press</td>
<td>0.72%</td>
</tr>
<tr>
<td>6</td>
<td>moulding press</td>
<td>0.23%</td>
</tr>
<tr>
<td>7</td>
<td>mechanical press</td>
<td>0.00%</td>
</tr>
<tr>
<td>8</td>
<td>de-lubrificator</td>
<td>0.00%</td>
</tr>
</tbody>
</table>

The analysis showed that the highest level of criticality in terms of maintenance, is associated with the drying department (38.44%) and extruder (31.72%). For this reason it was decided to carry out a more detailed analysis to study their characteristics.

Drying the product means to recover process solvents, which may be recycled to the plant. Also, dryers strongly influence overall production times. Drying is typically the most time-consuming step, so the efficiency of the drying process significantly affects the overall efficiency of the plant. Drying procedures generally run under vacuum to save energy, minimise the drying temperature, and protect operators and the environment. Liquid (usually process solvent) is evaporated from the wet product by heating the solvent above its boiling point corresponding to the absolute pressure. The vapour is pulled out by vacuum and recovered by a condensation system. Dryers typically have a dust filter to prevent particles from passing to the condenser and the vacuum pump.

Figure 4  Drying process

This department plays a primary role in the production cycle. A failure or partial recovery of the lubricant would result in a hard deposit of paraffin on the powder particles, with consequent problems of compaction of the powder in the subsequent pressing step.
The isopropyl alcohol recovery is affected by a piston vacuum pump, which according to the operators is the nerve centre of the system. The lack of physical redundancy in fact, means that any faults or wrong operations of the subsystem analysed may involve sensitive inefficiencies in terms of cost and quality of the process.

The piston pump for the vacuum, which therefore needs the maximum reliability, presents the following mechanical characteristics:

- motor power: 3 kW
- flow rate: 100 m³/h
- RPM: 250
- vacuum: 5.30 mbar
- total weight: 380 kg.

The electric motor rotates the flywheel which, through the distribution shaft, actuates the connecting rod, the piston, the rod of distribution and the drawer. The piston during its stroke, while it suctions from the slits of the gas cylinder, it empties, by the valves, the previously aspirated into the race in reverse. The pump operates in discontinuous mode for about 20–22 hours each day.

Maintenance manager needs to decide on how to allocate the available budget. The budget allocation should be based on the priority of the work and how the condition profile will change as a result of the allocation.

There are four options available for the allocation of maintenance budgets:

- **Option 1: First allocate funds to the assets in the worst condition.** This approach is called the ‘bottom up’ approach, because the allocation starts at the bottom of the condition scale. The focus is on the replacement and rehabilitation of buildings not in a desirable condition.

- **Option 2: Start allocating the available funds to the assets in the best condition.** This approach is called the ‘top down’ approach and starts with the allocation of funds to assets which have recently been maintained; does not exhibit any signs of deterioration. The focus is on the maintenance of buildings in desirable condition and the motivation for this approach is to keep the assets in that condition.

- **Option 3: Equal distribution of available funds to all condition categories.** This option is called the ‘balanced’ approach. The budget allocation to each condition category is based on the same ratio as the available budget to the required budget.

- **Option 4: Allocate funds on ad hoc basis to occupant making biggest noise.** This is the most likely option followed by most maintenance managers faced with a similar scenario. With MPA approach the maintenance manager normally ends up with not spending all the funds available.

In this study case, it is possible to underline how the dryer department needs more than 38% of the available resources, as illustrated in the Figure 5.
Under these aspects we could be excluded that a ‘balanced’ approach cannot be useful, because the remaining departments provide an allocation, in percent, significantly inferior than drying unit. Given that with the MCA method we are able to previously find out which department of a production process requires more maintenance attention, the solution more correct is the allocation shown in the option 4 where the funds are addressed in a specific way, without unnecessary expenses.

The budget for maintenance performance improvement (BMPI) allocated by the Company was €150000.00 additional to investments needed for the survival of the equipment. The total basic budget was equal to €80,000.00 (€10,000.00/unit).

Applying MCA method (Table 9 and Figure 5) we obtained the total maintenance budget allocation (Table 10).

Table 10  Allocated maintenance budget

<table>
<thead>
<tr>
<th>Units</th>
<th>MPI%</th>
<th>BMPI</th>
<th>Basic budget</th>
<th>TOTAL maintenance BUDGET</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit 2 Dryer</td>
<td>38.44%</td>
<td>€57,728.07</td>
<td>€10,000.00</td>
<td>€67,728.07</td>
</tr>
<tr>
<td>Unit 3 Extruder</td>
<td>31.72%</td>
<td>€47,426.01</td>
<td>€10,000.00</td>
<td>€57,426.01</td>
</tr>
<tr>
<td>Unit 8 Sintering</td>
<td>18.64%</td>
<td>€27,992.20</td>
<td>€10,000.00</td>
<td>€37,992.20</td>
</tr>
<tr>
<td>Unit 1 Mixer</td>
<td>10.26%</td>
<td>€15,412.38</td>
<td>€10,000.00</td>
<td>€25,412.38</td>
</tr>
<tr>
<td>Unit 5 Hydraulic press</td>
<td>0.72%</td>
<td>€1,096.17</td>
<td>€10,000.00</td>
<td>€11,096.17</td>
</tr>
<tr>
<td>Unit 7 Moulding</td>
<td>0.23%</td>
<td>€343.75</td>
<td>€10,000.00</td>
<td>€10,343.75</td>
</tr>
<tr>
<td>Unit 4 Mechanical press</td>
<td>0.00%</td>
<td>€0.00</td>
<td>€10,000.00</td>
<td>€10,000.00</td>
</tr>
<tr>
<td>Unit 6 De-lubrificator</td>
<td>0.00%</td>
<td>€0.00</td>
<td>€10,000.00</td>
<td>€10,000.00</td>
</tr>
</tbody>
</table>
6 Conclusions

By analysing the results of the case study, it is possible to note how the proposed model favours simplicity, since this is a tool for preliminary analysis, both in the mathematical treatment, as in the application. This feature allows a profitable use, without excessive use of resources. In addition, the generality of the introduced indicators determines the applicability to any type of industrial plant, regardless of its peculiarities. Moreover, the AHP drives indexes calculation, according to the characteristics of each analysed system.

By repetitively applying the analysis, the method can be also used to compare different maintenance strategies and to check the results.

Finally, it is important to note the similarities between the proposed method and FMECA. The two methods have a very similar logic, although using different indicators. While FMECA is focused on the analysis of failure modes, our approach takes into account a larger number of factors and is aimed to the analysis of units and machines in general. It should also be highlighted that, MCA can be used as a preliminary stage of more specific analysis on the machines.

References


Maintenance strategy design in a sintering plant


