Maintenance management and Optimization of the thermoforming process for the agri-food industry using the S\(^2\) model

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Abstract: The agri-food industry has been greatly enhanced in recent years with the introduction of process control and the automation [1] of certain links in the production chain. The seasons of the year in which these machines must be operational and show robust and reliable operation, have short durations (2 to 4 months) and are therefore greatly affected by unexpected failures that cause stops on the production lines. This paper attempts to expose a comparative advantages that can be obtained in terms of availability and efficiency in the thermoforming process. With the introduction of Industry 4.0 [2, 4] and the S\(^2\) model [5] and actuator control and early action, it is possible to optimize availability and efficiency ratios on thermoformer machines. Results show that it’s possible to reduce unexpected failures by means of this optimization tools. Two improvement strategies are outlined. Maintenance Management improvement model improves response to failures but does not optimize the useful life of the components. Algorithm life optimization based on S\(^2\) model optimizes service life and improves response to failure.

Keywords: Thermoforming process, Availability, Industry 4.0, IoT, Efficiency.

1. Introduction

Online manufacturing processes require high levels of availability and reliability for high productions in short seasonal periods of the year. It is very important to control and define the stops times to avoid the sudden appearance of breakdowns causing unexpected stops and non-compliance with manufacturing commitments.

In the agri-food sector [1] the manufacture of many products is carried out in periods of time closely linked to harvests and collections. This is a reality that must be borne in mind when designing and structuring the entire production process. Currently, factories must be prepared to meet an extraordinary volume of production and demand, always controlling quality and compliance with the correct sanitary measures required by the administration.

The advantages of IoT [2] enable real-time management in the cloud, making decisions based on the comparison proposed by algorithms developed to maximize the useful life of the components, guaranteeing the reliability of these decisions.

The final objective of this research is to obtain a relationship between the production function and the availability of the machines, so that the study of the reliability of their equipment provides an
availability status that allows guaranteeing production function and avoiding unexpected failures or not controlled during a production batch. In this way, the value chain [3] obtains the benefits of a more reliable service, with better quality and information [4] about their orders.

2. Case study and methodology

2.1. Thermoforming and ture filling machines
Thermoforming and tubs filling machines are one case among the many that exist. This type of machines is the object of this study. These machines are composed of several sub-processes from the management of the polymer film to the container and lid, as well as the dosage and final cut.

The sub processes involved in this machine are the following (see figure 1):

- Polymer dispenser roll for the container of the tub.
- Thermoformed thermal container conditioner.
- Thermoformer by mechanical compression and pressure.
- Rationing of the content by peristaltic pumps.
- Polymer dispenser roll for the lid of the tub container.
- Thermal adhesion of the lid of the tub to the thermoforming and filling container.
- Individualized cutting of the tubs for their subsequent logistical packaging.

The cycle time can vary between 6 and 12 tubs per second, depending on whether the machine is designed to manufacture 3, 6, 9 or up to 12 tubs simultaneously. Normally, the production is usually two rows simultaneously, then in a cycle, twice a series of 3, 6, 9 or 12 tubs can be manufactured. This affects the size, mold of the thermoformer, number of peristaltic pumps, rails for the row passage, size of the thermal bonder of the lid and size of the tub cutter.

Normal operation requires the constant coordination of all sub processes since a failure in one of them, means the loss of ongoing production.

From the thermal conditioner of the polymer for the thermoformer of the container, to the cutter for finished tubs, there is an axis in the lower part of the machine that with cams in synchronized positions, allow coordinated movements so that the process is controlled and at constant speed.

2.2. Description of the typical faults in the components
Table 1 shows a basic decomposition of the components of the machine subject to failure in the present work. A distinction is made between static or moving elements, the possible origin of a failure and the consequence of its failure.
### Table 1. Basic decomposition of components and faults.

| No. | Component                        | Type/Type | Fault Source                                           | Failure  |
|-----|----------------------------------|-----------|-------------------------------------------------------|----------|
| 1   | Master power switch              | Power Machine/static | Ambient condition, Power supplier event | Stop     |
| 2   | PLC                              | Control/static    | Ambient condition, Power supplier event | Stop     |
| 3   | HMI                              | Control/static    | Ambient condition, Power supplier event, Crash          | Stop     |
| 4   | Cromatic sensor                  | Sensor/static    | Ambient condition, Power supplier event, Crash          | Malfunction |
| 5   | Plug-in relay                    | Control device/static | Ambient condition, Power supplier event | Stop     |
| 6   | Command and signalling           | Control        | Ambient condition, Power supplier event, Crash          | Stop     |
| 7   | Safety limit switch              | Security/Static  | Ambient condition, Power supplier event                | Stop     |
| 8   | Safety relay                     | Security/Static  | Ambient condition, Power supplier event                | Stop     |
| 9   | Safety button                    | Security/Static  | Ambient condition, Power supplier event, Crash          | Stop     |
| 10  | Temperature controller            | Control/static   | Ambient condition, Power supplier event                | Stop     |
| 11  | Solid state relay                | Actuator/static  | Ambient condition, Power supplier event                | Malfunction |
| 12  | Thermal resistance               | Actuator/Dynamic | Ambient condition, Power supplier event, Global fatigue | Malfunction |
| 13  | Thermocouple sensor              | Control/Dynamic  | Ambient condition, Power supplier event, Global fatigue | Stop     |
| 14  | Tape drive                       | Actuator/Static  | Ambient condition, Power supplier event                | Stop     |
| 15  | Tape Motor                       | Motor/Dynamic    | Ambient condition, Power supplier event, Global fatigue | Stop     |
| 16  | Bronze cap                       | Structure/Dynamic | Ambient condition, Power supplier event, Global fatigue | Stop     |
| 17  | Linear axis                      | Structure/Dynamic | Ambient condition, Power supplier event, Global fatigue | Stop     |
| 18  | Lineal bearing                   | Structure/Dynamic | Ambient condition, Power supplier event, Global fatigue | Stop     |
| 19  | Pneumatic valve                  | Actuator/Dynamic | Ambient condition, Power supplier event, Pressure failure, failure valve | Malfunction |
| 20  | Pneumatic cylinder               | Actuator/Dynamic | Ambient condition, Power supplier event, Pressure failure, cylinder failure | Malfunction |
| 21  | Pressure sensor                  | Control/static   | Ambient condition, Power supplier event                | Stop     |
| 22  | Servo drive peristaltic pump     | Actuator/Dynamic | Ambient condition, Power supplier event                | Stop     |
| 23  | Peristaltic pump                 | Actuator/Dynamic | Ambient condition, Power supplier event                | Stop     |

### 2.3. Analysis of times and ratios used

The times involved in the favorable resolution of the failures and their mathematical expressions are the following:

- $TT_{RP}$ Time to replace component
- $TC$ Time to configure
- $TT_{MA}$ Time to mechanical adjustment
- $TT_{PR}$ Time to provisioning
- $MTTR$ Main time to repair
- $MTTF$ Main time to failure
- $MTBF$ Main time between failure
- $TT_{LR}$ Line restart time, defined by expert knowledge
- $T_{LP}$ Time lost production

\[
MTTR = TT_{RP} + TC + TT_{MA} + TT_{PR}
\]

\[
T_{LP} = MTTR + TT_{LR}
\]
MTBF = MTTR + MTTF  \tag{3}

With these times, two concepts are used, efficiency (4) and availability (5). Both concepts will be used as indicators of success in the preventive control of machine failures.

\[
\text{Efficiency} = \frac{T_{LP}}{MTTR + MTTF} \tag{4}
\]

\[
\text{Availability} = \frac{MTBF}{MTBF + MTTR} \tag{5}
\]

Setting the line restart time at 7200 seconds and with stable market values are used for the times in this machine, the following results are shown in table 2.

**Table 2.** Complete display of times, efficiency and availability. Times in seconds.

| Component                  | MTTR | TP | TC | TMA | TPR | MTTF | TLP | Efficiency | MTBF | Availability |
|----------------------------|------|----|----|-----|-----|------|-----|------------|------|--------------|
| Master power switch        | 14400| 3600| 0  | 0   | 0   | 10800| 28800| 99.71%     | 10014399 | 99.86%       |
| PLC                       | 435600| 3600| 86400| 0   | 0   | 345600| 450000| 95.69%     | 10435599 | 95.99%       |
| HMI                       | 435600| 3600| 86400| 0   | 0   | 345600| 450000| 95.69%     | 10435599 | 95.99%       |
| Cromatic sensor           | 176520| 3600| 120 | 0   | 0   | 172800| 190920| 96.31%     | 5176520  | 96.70%       |
| Plug                      | 14400| 3600| 0  | 0   | 0   | 10800| 28800| 99.43%     | 5014400  | 99.71%       |
| Command and signalling    | 14400| 3600| 0  | 0   | 0   | 10800| 28800| 99.43%     | 5014400  | 99.71%       |
| Safety limit switch       | 14400| 3600| 0  | 0   | 0   | 10800| 28800| 99.71%     | 10014399 | 99.86%       |
| Safety relay              | 14400| 3600| 0  | 0   | 0   | 10800| 28800| 99.71%     | 10014399 | 99.86%       |
| Safety button             | 14400| 3600| 0  | 0   | 0   | 10800| 28800| 99.71%     | 10014399 | 99.86%       |
| Temperature controller    | 435600| 3600| 86400| 0   | 0   | 345600| 450000| 95.69%     | 10435599 | 95.99%       |
| Solid state relay         | 176400| 3600| 0  | 0   | 0   | 172800| 190800| 96.31%     | 5176400  | 96.70%       |
| Thermal resistance        | 25500| 14400| 300 | 0   | 0   | 10800| 3700800| 98.93%     | 3726300  | 99.32%       |
| Thermocouple sensor       | 14700| 3600| 0  | 0   | 0   | 10800| 3700800| 99.22%     | 3715500  | 99.61%       |
| Tape drive                | 435600| 3600| 86400| 0   | 0   | 345600| 450000| 95.69%     | 10435599 | 95.99%       |
| Tape Motor                | 187200| 14400| 0  | 0   | 0   | 172800| 201600| 96.11%     | 5187200  | 96.52%       |
| Bronze cap                | 288000| 288000| 0  | 86400 | 0   | 172800| 775000| 96.24%     | 8038000  | 96.54%       |
| Linear axis               | 288000| 288000| 0  | 86400 | 0   | 172800| 762500| 96.18%     | 7913000  | 96.49%       |
| Lineal bearing            | 288000| 288000| 0  | 86400 | 0   | 172800| 750000| 96.12%     | 7788000  | 96.43%       |
| Pneumatic valve           | 176400| 3600| 0  | 0   | 0   | 172800| 190800| 98.13%     | 10176399 | 98.30%       |
| Pneumatic cylinder        | 176400| 3600| 0  | 0   | 0   | 172800| 190800| 98.13%     | 10176399 | 98.30%       |
| Pressure sensor           | 176700| 3600| 300 | 0   | 0   | 172800| 191100| 96.31%     | 5176700  | 96.70%       |
| Servo drive peristaltic pump | 435600| 3600| 86400| 0   | 0   | 345600| 450000| 95.69%     | 10435599 | 95.99%       |
| Peristaltic pump           | 547200| 14400| 0  | 14400| 0   | 518400| 561600| 89.88%     | 5547200  | 91.02%       |

Using the exponential model (6) the reliability of all the components is calculated in a time equal to MTTF. Figure 2 show the results.

\[
R(t) = e^{-\lambda t} \tag{6}
\]

Where \( \lambda \) factor is the inverse value of MTBF if we consider we are in constant fatigue of components.
reduce the lost production time as much as possible but guaranteeing the proper functioning of the

The following table shows the best strategies proposed to achieve better results. The objective is to

| COMPONENT                  | Without MMI | With MMI | AV MMI |
|----------------------------|-------------|----------|--------|
| Efficiency                 | Availability| Efficiency | Availability | Efficiency | Availability |
| Master power switch.       | 99.71%      | 99.86%   | 99.82% | 99.96%   | 0.10%       | 0.10%       |
| PLC                        | 95.69%      | 95.99%   | 98.96% | 99.11%   | 3.27%       | 3.12%       |
| HMI                        | 95.69%      | 95.99%   | 98.96% | 99.11%   | 3.27%       | 3.12%       |
| Cromatic sensor.           | 96.31%      | 96.70%   | 99.63% | 99.92%   | 3.32%       | 3.22%       |
| Plug-in relay              | 99.43%      | 99.71%   | 99.63% | 99.92%   | 0.21%       | 0.21%       |
| Command and signalling     | 99.43%      | 99.71%   | 99.63% | 99.92%   | 0.21%       | 0.21%       |
| Safety limit switch        | 99.71%      | 99.86%   | 99.82% | 99.96%   | 0.10%       | 0.10%       |
| Safety relay               | 99.71%      | 99.86%   | 99.82% | 99.96%   | 0.10%       | 0.10%       |
| Safety button.             | 99.71%      | 99.86%   | 99.82% | 99.96%   | 0.10%       | 0.10%       |
| Temperature controller     | 95.69%      | 95.99%   | 98.96% | 99.11%   | 3.27%       | 3.12%       |
| Solid state relay          | 96.31%      | 96.70%   | 99.63% | 99.92%   | 3.32%       | 3.22%       |
| Thermal resistance         | 98.93%      | 99.32%   | 99.21% | 99.60%   | 0.28%       | 0.28%       |
| Thermocouple sensor        | 99.22%      | 99.61%   | 99.50% | 99.89%   | 0.28%       | 0.28%       |
| Tape drive                 | 95.69%      | 95.99%   | 98.96% | 99.11%   | 3.27%       | 3.12%       |
| Tape Motor                 | 96.11%      | 96.52%   | 99.42% | 99.71%   | 3.31%       | 3.19%       |
| Bronze cap                 | 96.24%      | 96.54%   | 98.35% | 98.55%   | 2.11%       | 2.01%       |
| Linear axis                | 96.18%      | 96.49%   | 98.32% | 98.53%   | 2.14%       | 2.04%       |
| Linear bearing             | 96.12%      | 96.43%   | 98.29% | 98.51%   | 2.18%       | 2.07%       |
| Pneumatic valve            | 98.13%      | 98.30%   | 99.82% | 99.96%   | 1.69%       | 1.66%       |
| Pneumatic cylinder         | 98.13%      | 98.30%   | 99.82% | 99.96%   | 1.69%       | 1.66%       |
| Pressure sensor            | 96.31%      | 96.70%   | 99.63% | 99.92%   | 3.32%       | 3.22%       |
| Servo drive peristaltic pump| 95.69%      | 95.99%   | 98.96% | 99.11%   | 3.27%       | 3.12%       |
| Peristaltic pump           | 89.88%      | 91.02%   | 99.14% | 99.42%   | 9.26%       | 8.40%       |

3. Strategies to follow to improve results
The following table shows the best strategies proposed to achieve better results. The objective is to reduce the lost production time as much as possible but guaranteeing the proper functioning of the
components.

- **MMI**: Maintenance management improvement model.
- **AOP**: Algorithm life optimization based on $S^2$ model [5] with maintenance advises.

The MMI strategy is based on having stocks in advance, then it supposes a better response to unexpected failures, but it does not allow optimizing the useful life of the components before being replaced. This aspect is resolved by the AOP strategy, which also improves MTTF. The use of new materials can increase the useful lifetime.

The $YWF$ parameter is defined as years without failures, and it is used to monitor that the mean time between failures corresponds to more than one productive year, so that any preventive action can be planned at the best times without causing production stoppages.

4. **Maintenance management improvement (MMI) model**

This is a strategy based on the supply of components, would suppose a considerable reduction in the value of MTTR, and consequently, in the value of the efficiency and the availability. Table 4 shows the results of substituting the supply time for a residual search time in own stock.

The comparison of proposed scenarios provides an average increase in efficiency more than 7.5% and availability by 8.5%.

![Figure 3. Improvements in efficiency and availability using MMI strategy.](image)

Table 5. Sensors and components used for the model.

| Sensor | Description                        | Components affected |
|--------|------------------------------------|---------------------|
| SA1    | % Humidity inside control panel    | 1, 2, 3, 5, 8, 10, 11, 14 |
| SA2    | $C^\circ$ temperature inside control panel | 1, 2, 3, 5, 8, 10, 11, 14 |
| SA3    | Voltage RMS in IGBT                | 1, 2, 3, 4, 5, 8, 10, 12, 14, 15, 19, 20, 21, 22, 23 |
| SA4    | Vacuum sensor for Thermoformer tub| 10, 12, 13, 16, 18, 19, 20, 21 |
| SA5    | Volumetric sensor for peristaltic pumps | 22, 23 |
| SA6    | Micro laser measurement, side front| 14, 15, 16, 17, 18 |
| SA7    | Micro laser measurement, side rear | 14, 15, 16, 17, 18 |

5. **Algorithm life optimization (AOP) with maintenance advises**

This strategy allows to modify the MTTF by analyzing the behaviour of measurements from various
sensors, a reasonable modification of the MTTF of each component can be established. In this way, it
could be possible to optimize the useful life of each component. The operation of this strategy is
compatible with maintenance decisions, so that conclusions of the previous strategy can be applied at
certain times. Table 5 indicates proposed sensors and component group that they affect.

All sensors provide an analog output signal. A datalogger oversees monitoring, recording, and
treating the signals in real time.

5.1. Mathematical model of the algorithm
The system records a value every 10 duty cycles. Later it calculates its average value and saves them
(7). This operation is carried out 100 times, so that at the end of cycle 1000, 100 average values will be
available for each parameter.

\[
T_{1,SA1} = \frac{\sum_{i=1}^{10} SA1_i}{10}, T_{2,SA1} = \frac{\sum_{i=11}^{20} SA1_i}{10}, \ldots, T_{100,SA1} = \frac{\sum_{i=91}^{100} SA1_i}{10}
\] (7)

Each sample of 100 values is evaluated for whether there is a dispersion of values that indicates that
an error may occur in the measurement or in the sensor. Rejection criteria such as Chauvenet or similar
are used for them. Once the sample is validated, the statistical values corresponding to a Normal
Gaussian distribution are calculated, as the average (8) and the variance (9).

\[
\bar{X}_{SA1,100} = \frac{\sum_{i=1}^{100} T_{i,SA1}}{100}
\] (8)

\[
\sigma^2_{SA1,100} = \frac{\sum_{i=1}^{100} (T_{i,SA1} - \bar{X}_{SA1,100})^2}{100-1}
\] (9)

The following expression (10) is the dynamic adjustment factor, DFA of MTTF, and is obtained for
each component.

\[
DFA = \left[ \frac{A - (\bar{X}_{SA1,100} - 0.67\times\sigma_{SA1,100})}{k} \right]
\] (10)

where:

- \( A \) is the nominal value of the measurement in correct operation.
- \( k \) is the model adjustment value that differs in each given sensor according to the amount of
  valid values that in each case may be correct.
- The value 0.67 corresponds, according to the normal Gaussian distribution with a confidence
  level of 50%. A restrictive level is initially proposed. This value admits correction up to the
  value 3 which would suppose a confidence interval of 99.7%.

To correct any anomaly that arises unexpectedly, it is proposed to use an alarm value (11) in each
sensor that is active during the entire operating time of the machine. Each sensor has a coefficient \( S \) that
defines the alarm level.

\[
ALARM VALUE \ SA_1 = S \times A
\] (11)

The final objective of this model is to obtain the reliability of each component every 1000 cycles by
adding sensors whose evolution of values and dispersions may indicate a malfunction of the system.
Exponential or Weibull calculation models can be used for this purpose, depending on the actual state
of wear of each component.

6. Results and conclusions
Most of the machines that process products and have complex threads, must have an adequate
management of their maintenance that, as far as possible, leads to high rates of efficiency, availability,
and reliability.
Strategy MMI can only minimize the established times for provisioning, repair, configuration and/or mechanical adjustments. Its use brings extra costs, benefits but the improvement is limited. In this case an average increase in efficiency more than 7.5% and availability by 8.5%.

Strategy AOP make it possible to optimize the operating time of the components, monitoring sensor values whose value management can extend the useful life of the components and predict the ideal replacement time based on known repaired or programmed stop times.

The implementation of process availability and quality control techniques provide factories with the ability to adapt on demand, respond with constant quality and report in real time the status of compliance with their commitments. Therefore, factories increase their competitiveness in the market.

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