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Improving operation of the croissant production line through overall equipment effectiveness (OEE)

A case study

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Abstract

Purpose – Overall equipment effectiveness (OEE) is a metric for estimating equipment effectiveness of the industrial systems. The purpose of this paper is to identify maintenance improvement potentials using an OEE assessment within the croissant production line.

Design/methodology/approach – The present work is carried out by analyzing the failure and repair data of the line. The failure data cover a period of 15 months. During this period the croissant production line usually operates over the entire day (24 h per day) in three 8-h shifts per day, and pauses at the weekends. Descriptive statistics of the failure and repair data for the line based on scheduled and unscheduled interruptions were carried. Moreover, the actual availability (*A*), performance efficiency (*PE*) and quality rate (*Q*) measures, together with the complete OEE for each working day for the croissant production line, were shown.

Findings – The main objectives are to understand the operation management of the croissant production line, and to measure the OEE characteristics in precise quantitative terms. OEE analysis can help the company to identify the primary problems concerning the *A*, *PE* and *Q* and acts immediately.

Originality/value – This paper presents a successful evaluation of OEE which will provide a useful guide to aspects of the production process, which identifies the critical points of the line that require further improvement through effective maintenance strategy (i.e. total productive maintenance). Moreover, the analysis provides a useful perspective and helps managers and engineers make better decisions on how to improve manufacturing productivity and quality.

Keywords Reliability, Statistical analysis, Total productive maintenance (TPM), Performance indicators, Failure data

Paper type Case study

1. Introduction

To be competitive, manufacturers provide excellent reliability and quality of their equipment at competitive prices. In order to possess highly reliable machines to make smooth manufacturing processes certain, many organizations have implemented total productive maintenance (TPM) as the enabling tool to maximize the effectiveness of equipment (Bon and Lim, 2011). Maintenance and its management has moved from being considered a “necessary evil” to being of strategic importance for most competitive organizations around the world (Fraser *et al.*, 2015; Cooke, 2000; Zio, 2009). One of the most crucial and widespread applied tools of performance measurement in the manufacturing industry is overall equipment effectiveness (OEE) (Wudhikarn, 2013). OEE is the key measure of both TPM and lean maintenance (Anvari *et al.*, 2010).

The OEE reveals the hidden costs associated with the efficiency of the equipment. OEE is defined as a measure of total equipment performance, that is, the degree to which the

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equipment is doing what it is supposed to do (Williamson, 2006). A comparison between the expected and current OEE measures can provide the much-needed impetus for the manufacturing organizations to improve the maintenance policy and affect continuous improvements in the manufacturing systems (Wang, 2006). Thus, the OEE provides a quantitative metric based on the elements availability, performance and quality for measuring the performance effectiveness of individual equipment or entire processes (Garza-Reyes, 2015). OEE is the TPM metric for measuring equipment effectiveness or productivity. Variations for calculating OEE are in use; however, most are consistent in identifying three major elements of OEE, which are availability, performance efficiency and quality rate (Bon and Lim, 2011). The firms, under ideal conditions, should have availability $A > 0.90$, performance efficiency $PE > 0.95$ and rate of quality $Q > 0.99$. These would result an overall $\text{OEE} > 0.84$ benchmark, which is considered as world-class performance (Zuashkiani *et al.*, 2011; Jonsson and Lesshammar, 1999).

In the food industry, the production process requires non-stop operation of automatic production line equipment. A stoppage in a production line, due to a failure of the equipment, causes a drop in the productivity as well as quality problems on the products (Liberopoulos and Tsarouhas, 2002). In this paper, the gap between theory and practice was brought with the collection and the analysis of failure data for an automated croissant production line under real working conditions that is representative in this section. In particular, the OEE of the line that will provide a useful guide to aspects of the production process was computed. The line usually operates over the entire day (24 h per day) in three 8-h shifts per day, and pauses at weekends. Descriptive statistics of the failure and repair data for the line based on scheduled and unscheduled interruptions were carried out. The identification of the critical points of the line that require further improvement through effective maintenance strategy (i.e. TPM) was provided. The analysis provides a useful perspective and helps managers and engineers make better decisions on how to improve manufacturing productivity and quality.

This paper is structured as follows: Section 2 deals with the literature review of the OEE, the methodology is shown in Section 3. In Section 4, the OEE theory is introduced, the case study with the description of the production line and the field failure data of the croissant production line are displayed in Section 5. In Section 6, the data collection and operations management for the production line are presented. Statistical analysis of the failure and repair data is shown in Section 7. The calculation of the OEE for the croissant production line is computed in Section 8, and finally in Section 9, the conclusions are drawn.

2. Literature review

2.1 Productivity, efficiency and effectiveness

Productivity is one of the most fundamental and crucial determinants of the production systems. Productivity measurement helps identify problems and find solutions to improve system performance (Nachiappan and Anantharaman 2006; Braglia *et al.*, 2008; de Ron and Rooda, 2005). Sumanth (1979) considered productivity as a summation of total tangible outputs divided by total tangible inputs. Therefore, productivity is defined as “the quality of being efficient,” and is a measure of the rate of production, output per unit input. Productivity and efficiency are often used more or less synonymously (Kling, 2006). Efficiency measures how well a firm performs relative to the best practice, or the most output which is obtainable from a given input level with the given production technology (Yu, 2016). Efficiency can be seen as the “production of required output at a perceived minimum cost, measured by the ratio of quantity of resources expended to plan,” whereas effectiveness can be seen as a measure of “how closely an organization’s output meets its goal and/or the customer’s requirements” (Schmidt and Finnigan, 1992). Campbell (1990) defined effectiveness as “the evaluation of the results of the performance” meaning how well a company is performing to meet their goals. In addition, Schmidt and Finnigan (1992) defined effectiveness as being able to organize and meet customer requirements. From a conceptual point of view, Pritchard (1992) defined productivity as a combination of efficiency and effectiveness, where efficiency is the maximum generation of outputs with the minimum amount of inputs. Efficiency and effectiveness are the central terms used in assessing and measuring the performance of organizations (Mouzas, 2006).

However, for the managers, these terms might be synonymous but each has their own distinct meaning (Kumar and Gulati, 2009). It is known that Drucker (1977) distinguished efficiency and effectiveness by associating efficiency with "doing things right" and effectiveness with "doing the right things." Hence, a measure of efficiency assesses the ability of an organization to attain the output(s) with the minimum level of inputs. More precisely, efficiency is primarily concerned with minimizing the costs and deals with the allocation of resources across alternative uses, and merely not a measure of a success in the marketplace but a measure of operational excellence in the resource utilization process (Achabal *et al.*, 1984). While commenting on effectiveness, Keh *et al.* (2006) observed that a measure of effectiveness assesses the ability of an organization to attain its pre-determined goals and objectives. In other words, an organization is effective to the degree to which it achieves its goals (Asmild *et al.*, 2007). To sum up, effectiveness is the extent to which the policy objectives of an organization are achieved. It must be noted that even though efficiency and effectiveness are two mutually exclusive components of overall performance measure, it is possible they may influence each other. To be more specific, effectiveness can be affected by efficiency or can influence efficiency as well as have an impact on overall performance (Ozcan, 2008).

2.2 Overall equipment effectiveness (OEE)

OEE has been widely used in industry in order to measure equipment performance (Kumar *et al.*, 2013). OEE consists of three separate components (availability, performance and quality) where each aims at an aspect of the process that can be improved. More recent publications argue that OEE figures are commonly 15–25 percent below the targeted level, thus constituting one of the largest problems in industry today (Parida *et al.*, 2014). The output assessment data lead to a decision making for optimum management of the equipment and production systems on behalf of the industries (Garza-Reyes *et al.*, 2010). The use of metric systems is necessary for this purpose (Nachiappan and Anantharaman, 2006). OEE is able to measure performance, identify improvement opportunities and direct the focus of improvement efforts in areas related to equipment efficiency and effectiveness (Kumar *et al.*, 2014). OEE quantifies how well a production system performs relative to its designed capacity, during the period of operation. A survey conducted by Bamber *et al.* (2003) reports that OEE is often used as a means of improving the output of a company since it focuses on quality, productivity and use of the equipment at the same time. Benjamin *et al.* (2015) proposed the OEE to reduce or eliminate the speed loss in a lean manufacturing environment. Sonmez *et al.* (2018) considered two types of uncertainty in production speed and stoppage duration measurements, which are used in calculating OEE components. Implementation of the methods is illustrated using two real-world examples and software for practitioners was provided. Binti Aminuddin *et al.* (2016) explored different managerial conditions related to the implementation and use of OEE. Data were collected through a survey questionnaire taken by 139 manufacturing organizations worldwide. Braglia *et al.* (2018) proposed a novel methodology that seizes upon OEE's straightforward and easy-to-use structure to address the problem of measuring the effective use of materials within a factory.

The cost and financial implications of the quality of the production systems are a subject of a lot of research. When it comes to issues such as reliability, availability, safety, quality and cost-effectiveness levels of plant and equipment, there is no doubt that the cost of maintenance can be high, often representing a significant portion of recurrent budgets (Ahmadi *et al.*, 2010; Al-Najjar and Alsyouf, 2003). Warburton *et al.* (1998) reported that failures reduce the production and profits of a company. Munoz-Villamizer *et al.* (2018) proposed a new methodology for evaluating the effectiveness of urban freight transportation systems using the OEE metric, a well-known rate used in the lean manufacturing framework. Gupta and Vardhan (2016) investigated how increase in sales volume has evolved by improving the OEE of machines, plant productivity and production cost through TPM initiatives in a reputed tractors manufacturing industry in India. Muchiri and Pintelon (2008) concluded that the tools of measuring the quality and effectiveness of a production system can help in the management of overtime expenses and further production lines, with the ultimate consequence of the reduction of the running cost of an enterprise. Moreover, Kwon and Lee (2004) presented a new calculating methodology for estimating the quantitative monetary managerial effects as a result of TPM activities. The suggested methodology is to calculate the total saving monetary amount composed of contribution profit and saving costs that are obtained by improving the OEE of processing type equipment. On the other hand, Zuashkiani *et al.* (2011) indicated the potential of OEE, in improving management practices of resources. Thus, the maintenance function affects all OEE constituting measures, i.e. availability is heavily affected by maintenance. All planned shutdown and maintenance activities reduce equipment availability and, hence, affect the company's OEE. Colledani and Tolio (2011) suggested an evaluation method for the production quality, setting the basis for the development of models for control charts, inspection points and magnitude of regulators. Hwang *et al.* (2017) investigated the effect of the Internet of Things workability on the OEE, based on the final results of the simulation, both for the planned and actual productions. Saleem *et al.* (2017) formulated a benchmark to increase the tyre curing press production rate while minimizing tyre curing press downtime and maintenance cost with the help of a maintenance management technique based on OEE. Zammori (2014) aimed to extend the capabilities of the OEE, so as to capture the day-to-day fluctuations to which manufacturing performances are subjected. Wudhikarn (2016) described the overall equipment cost loss (OECL) methodology and an implementation of this methodology, to compare the outcomes of OECL with those of OEE, and finally to identify the benefits offered by this new methodology.

There is strong correlation between OEE and TPM. The concept of TPM was launched by Nakajima (1988) who proposed OEE as a metric for evaluating the progress of TPM (Jeong and Phillips, 2001). According to Jain *et al.* (2012), TPM implementation does not only improve OEE of large industries but also improves OEE of small scale industries by improving availability, performance and quality rate of machines. The strategic outcome of TPM implementations is the reduced occurrence of unexpected machine (equipment) breakdowns that disrupt production and lead to losses, which can exceed millions of dollars annually (Gosavi, 2006). The objective of TPM is to reduce the breakdowns, increasing the production rate as well as the performance of the system. TPM maximizes equipment effectiveness through employee involvement, and integrates the use of autonomous maintenance and small group activities to advance equipment reliability, maintainability and productivity (Brah and Chong, 2004; Pun *et al.*, 2002). Sonmez and Testik (2017) mentioned that a vital component of continuous improvement in production environments is measuring performance. For instance, in the TPM philosophy, OEE is used as a key performance indicator. Tsarouhas (2007) developed a methodology based on TPM for increasing production rate, improving the quality of the products and providing a healthier and safer work environment. Sharma and Trikhab (2011) have concluded that TPM was chosen as an effective maintenance strategy to improve OEE of production machines. Ramlan *et al.* (2015) mentioned that OEE measurement is inspired by the TPM and used as a key machine performance tool which measures availability, performance and quality rate. TPM is a resource-based approach where all employees are responsible for contributing to avoid equipment deterioration, breakdowns, failures and stoppages (Mad Lazim and Ramayah, 2010). The TPM focuses on the equipment of the system in order to avoid inconvenience related to quality, efficiency, inventory, safety and health. Moreover, TPM initiatives in production help in streamlining the manufacturing and other business functions, and garnering sustained profits (Ahuja and Khamba, 2007). Wakjira and Singh (2012) have concluded that the TPM implementation in any organization enhances the OEE by increasing equipment availability, decreasing rework and rejection. Phogat and Gupta (2017) identified the main problems in maintenance operations and compare these problems with those in manufacturing operations as found in the literature for effective maintenance. They concluded that lack of top management support, lack of measurement of OEE, lack of strategic planning and implementation and many more problems are the biggest problems in maintenance operations as well as manufacturing operations.

OEE can have various applications according to literature reviews. There are several studies in the semiconductive industry (Huang *et al.*, 2003), metal industry (Anvari *et al.*, 2010), rails (Åhrén and Parida, 2009) and airbag safety devices to the automotive industry (Dal *et al.*, 2000). However, the literature in food industry is very limited, and there are few papers, such as Tsarouhas and Arvanitoyannis (2012), that investigated the relationship between the management of a factory and the limoncello production line. The production line did not reach the 85 percent goal, due to speed losses, errors and defective products which were attributed to the maintenance practices of the company. The installation of a TPM program was suggested, as well as the optimization of spare part management and the training of technicians and operators of the company. In another study, Tsarouhas and Arvanitoyannis (2010) similarly concluded and stressed the importance of the maintenance policies for the best possible operation reliability, and the parallel productivity increase, effectiveness of the production line and reduction of the production cost. Zennaro *et al.* (2018) carried out an innovative micro downtime data collection and statistical analysis in the food and beverage sector; it introduces a numerical indicator called "Cost Performance Indicator" to estimate the performance improvement of investment activities. The study reveals the importance and incisiveness of short process downtimes in automated production systems in terms of OEE reduction. Tsarouhas (2013a) calculated the OEE of the limoncello production line over a period of eight months based on failure data. Mansour *et al.* (2013) developed a practical method to evaluate operational performance of workover rigs and present an approach to measure the OEE based on results of the evaluation method at the Sarir Oilfield in Libya. In another study, Tsarouhas (2013b) investigated the relationship between the factory management and the operation of the mozzarella production line through the OEE. Finally, Tsarouhas (2015) computed the OEE as a metric for evaluating the progress of TPM of a yogurt production line in a medium-sized Italian company.

3. Methodology

The aim of this research is to compute OEE in an automated croissant production line in order to estimate the current operations management. The data collection was undertaken over 15 months and concerns the documentation of system report in every shift. The based steps of the methodology are as follows:

(1) collection of data that provide information about the design and use of the respective performance measurement systems during the production process, i.e. downtime losses, planned downtime (planned maintenance, cleaning, research and development (R&D) trial, etc.), changeover, number of defects, etc.;

(2) calculation of OEE characteristics, i.e. A, PE and Q, as well as the OEE. Through the data it should be possible to identify the major loss by inspecting each of six categories losses related to OEE separately;

(3) calculation of maintenance time ratio, α, which is related to reliability and maintainability of the line;

(4) investigating strategic management tools and techniques to reduce losses that are related with OEE characteristics as well as the performance of the croissant production line; and

(5) after the application of a widespread operation management, re-calculation of the α, OEE with their characteristics of the line is necessary to measure its efficiency and productivity.

The most important benefit of methodology is the uninterrupted observation of the production procedure through indicators and its utilizations which bring about an endless improvement cycle within the principles of total quality management.

The main objectives are as follows:

- identify the critical workstations/machines, which require further improvement through effective maintenance policies (*Obj*1);
- to identify OEE characteristics that do not meet a world-class workstation/machine performance (OEE) benchmark (*Obj*2);
- to assess failure data of an automated croissant production line under real working conditions (*Obj*3); and
- to propose suggestions in order to improve workstations/machines performance (OEE) as well as the production line (*Obj*4).

4. Measurement of overall equipment effectiveness (OEE)

The OEE provides a quantitative metric for measuring the performance effectiveness of individual equipment or entire processes. The OEE is accepted as a measurement of internal efficiency (Jonsson and Lesshammar, 1999) and it is the true measure of the value added production by equipment (Chowdhury and Mandal, 1995). The OEE is a function of a number of mutually exclusive characteristics (Huang *et al.*, 2003), such as availability (A), performance efficiency (PE) and quality rate (Q). It is a three-part analysis tool for equipment performance based on its availability, performance and quality rate. It is used to identify the related losses of the equipment, with the purpose of improving total asset performance and reliability (Muchiri and Pintelon, 2008).

The losses that reduce the effectiveness of the equipment could be classified into six major categories as below (Nakajima, 1988):

(1) equipment failure losses contain failures modes that stop the normal operation of the equipment and reduce its production rate;

(2) setup and adjustment losses, that is, time losses which occur when production of one item ends and the equipment is adjusted to meet the requirements of another item;

(3) losses of minor stoppage and idle: these occur when the production is interrupted by a temporary malfunction or when a machine is idling;

(4) losses of reducing speed, because of the drop in speed from the nominal speed of the equipment;

(5) losses of defect (or rework) in process; and

(6) reduced performance, losses of materials because of differences in the weight of input and output.

The first two losses are defined as time losses that are used for calculating the availability, A, of an equipment. The third and fourth losses are speed losses that measure the performance efficiency, PE, of an equipment. The last two losses are regarded as quality losses; these losses directly affect the quality rate, Q.

Availability, A, can be expressed as the ratio of actual operating time to loading time. Thus:

$$A = \text{Operating time}/\text{Loading time} = \text{Loading time–Downtime}/\text{Loading time}, \quad (1)$$

where loading time is the planned time available per time period (day, week or month) for production operations, and operating time is calculated from loading time minus the downtime. Downtime is the total time that the system is not operating because of equipment failures, setup/adjustment requirements, exchange of dyes and other fixtures, etc. Availability can be expressed as the ratio of actual operating time to loading time.

The performance efficiency, PE, can be estimated from:

$$PE = \text{Net operating time}/\text{Operating time} = \text{Cycle time} \times \text{Processed amount}/\text{Operatingtime}, \quad (2)$$

where net operating time is the time during which equipment produces at the standard production rate. To calculate net operating time, subtract performance time losses from the operating time. Performance time losses consist of normal production losses (production rate reduction due to start-up, shutdown and changeover) and abnormal production losses (production rate reductions due to abnormalities). Net operating time is the processed amount multiplied by the actual cycle time.

The quality rate, Q, is defined as follows:

$$Q = \text{Processed amount–Defect amount}/\text{Processed amount}, \quad (3)$$

where processed amount refers to the number of items processed per time period (day, week or month). The defect amount represents the number of items rejected due to quality defects that require rework or become scrapped.

Therefore, the OEE can be calculated as follows:

$$\text{OEE} = \text{Availability} \times \text{Performance efficiency} \times \text{Quality rate} = A \times PE \times Q. \quad (4)$$

Ericsson (1997) reported that acceptable OEE performance can vary between 30 and 80 percent. Further research refers to OEE figures of between 60 and 75 percent, respectively (Ljungberg, 1998).

5. Description of the croissant production line

The company is one of largest manufacturers of bakery products in Europe, making croissants on 13 specialized processing lines. All lines are similar, but for the sake of preciseness in our presentation, we focus on a particular line, which is representative of those used in the sector. The croissant production line in study consists of several workstations in series integrated into one system by a common transfer mechanism and a common control system. The movement of material between stations is performed automatically by mechanical means (Liberopoulos and Tsarouhas, 2002). There are eight workstations in making croissants: kneading, forming, proofing, baking, injecting, lifting, returning trays and wrapping. Each workstation takes place on a separate section of the processing line (Figure 1). The process flow of the line is as follows.

In Workstation 1 (WS 1): flour, water and ingredients in small quantities such as sugar and yeast are fed into the removable bowl of the mixer machine (M1.1). Upon completion of kneading, the bowl is unloaded from the mixer machine and is loaded onto the

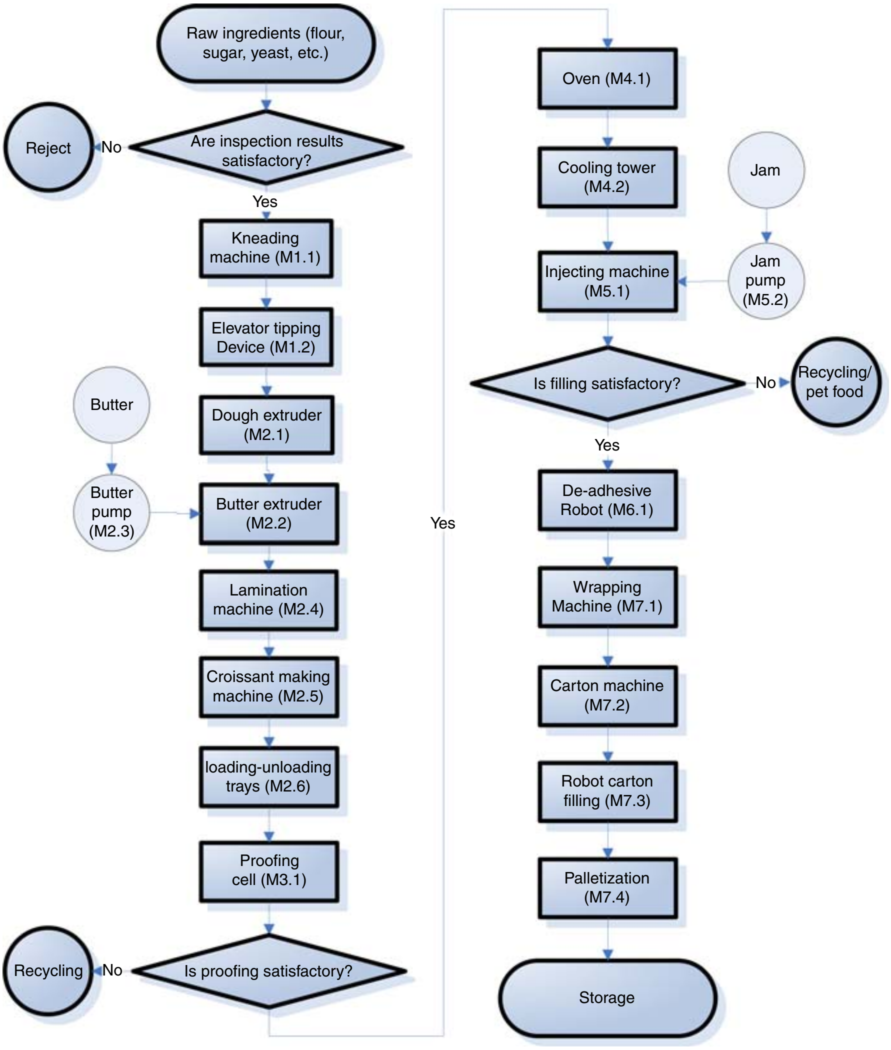

Figure 1.
The croissant
flow diagram

elevator-tipping device (M1.2) that lifts it and tips it over to the dough extruder of the lamination machine in the next workstation.

In Workstation 2 (WS 2): the dough, through the dough extruder (M2.1) that is fed into the lamination machine (M2.4), is laminated, buttered via a butter extruder (M2.2) through the butter pump (M2.3), folded, reduced in thickness by a multi-roller, and refolded a few times by a retracting unit to form a multi-layered sheet. The multi-layered dough is then automatically fed into the croissant-making machine (M2.5), where it is cut into triangles. Finally, the triangles are rolled into the form of the final product. At the exit of the croissant-making machine, the croissants are laid onto metal trays, and the trays are automatically inserted into carts (M2.6).

In Workstation 3 (WS 3): the carts are moved into the proofing cell (M3.1), where they remain under strict uniform temperature and humidity conditions for a precise amount of time. There, the croissants rise to their final size.

In Workstation 4 (WS 4): the carts are exited from the proofing cell to the oven (M4.1). Then, the trays are automatically unloaded from the carts and are placed onto a metal conveyor that passes through the oven. The trays remain in the oven for a precise amount of time until the croissants are baked. Upon exiting from the oven, the trays stay on the conveyor and trace a trajectory for a certain time in order for the croissants cool down (M4.2).

In Workstation 5 (WS 5): the croissants are filled through the pump (M5.2) with chocolate, cream or jam, by an automatic injecting machine (M5.1).

In Workstation 6 (WS 6): the croissants are automatically lifted by a robotic system (M6.1) from the trays onto the conveyor belt to the flow-packed of the wrapping machine in the next workstation.

The Workstation 7 (WS 7) of the croissant production line contains four-machines, the horizontal electronic wrapping machine (M7.1) where the croissants are flow-packed and sealed, the carton machine (M7.2), robot carton (M7.3) and palletizer (M7.4). The empty trays are automatically returned to the croissant-making machine (WS 8).

The Workstations 1–8 describe the entire croissant production line that is subject to failures. However, besides the failures of the equipment that may be characterized as "internal failures," there are also failures due to the exterior environment which affect the entire line. These failures may be characterized as "external failures," and are described in the ninth workstation. This workstation has four "external-machines" which correspond to the electric power, water, gas and air supply. Failures at Workstation 9 (WS 9) are not that frequent, but they are important because they affect the entire line. The most significant of these failures is the failure of the electric power generator that temporarily supplies the system with electricity in case of an electric power outage.

6. Data collection and operations management

The production line functions on a daily basis, 24 h, equally divided into three 8-h shifts. It does not usually function during weekends and holidays. The technical department has collected data that cover a 15-month period, that concern the documentation of system failures in every shift. These data refer to a total of 265 working days. The records included the failures that had occurred per shift, the corrective action taken to repair the failure, the downtime and the exact time of failure. The types of failures that happen in each workstation are mechanical, electrical, hydraulic, pneumatic and electrical failures. It is possible to have the same failure mode in different workstations, i.e. change bearings in the mixer (M1.1 of the WS 1) and change bearings in the dough extruder (M2.1 of the WS 2). In each case, the records also included the type of failure, the machine and the workstation that failed. There are often trials in a production line, for the improvement of the quality of the existing products, or the creation of new ones. Very often though, the final product is altered, with respect to the size, shape, form or filling. These interruptions greatly affect the OEE indices, especially of the production line output.

Data from 555 failures and 142 pauses (changeovers and trials of products) over a period of 265 production line working days were collected in total. The experimental time was 6,144 h or 768 shifts or 368.840 min. During this time, 119 changeovers in the filling or the form of the croissant took place, and 23 trials by the R&D department. Changeover is the adjustment time between one batch ends to next batch run.

In Table I, the experimental data for the croissant production line were summarized. As scheduled interruption the total time for coffee breaks is taken under consideration (about 20 min for shift) plus the total time for changeovers and trials of products from the R&D department. Unscheduled interruptions (i.e. downtime losses caused by unexpected breakdowns) are the time to repair the failures, meaning the total time to repair or 23,332 min. The following conclusions can be reached: first, the line produces for 88.14 percent (325,103/368,840), while the remaining 11.86 percent (43,737/368,840) was engaged for scheduled and unscheduled interruption. Second, the scheduled interruption in the production line accounts for 5.53 percent (20,405/368,840) of the total experimental time. Third, the unscheduled interruption of the line that are repair times equals to 6.33 percent (23,332/368,840) of total experimental time, and fourth, the changeovers of products occur for 1.17 percent (4,305/368,840), whereas the trials for 0.37 percent (1,365/368,840) of the total experimental time.

In Figure 2, the Pareto diagram for all failures presented in a croissant production line at each workstation is shown. The purpose of the Pareto diagram is to highlight the most important workstations in respect to the failures number that is presented on each of them. The left-side vertical axis of the Pareto diagram is the frequency of the failures, the right-side vertical axis of the diagram is the cumulative percentage, and the horizontal axis of the diagram is the workstations. The following observations were made: the forming (WS 2) has the highest number of failures 22 percent; the second important is the proofing cell (WS 3) that has 17 percent of failures; and the forming (WS 2), proofing (WS 3) and wrapping (WS 7) in the diagram stand for 55.1 percent of all the failures of the croissant production line. Therefore, the managers and engineers of the croissant production line must attend those workstations because they influence the reliability and the efficiency of the line.

7. Statistical analysis

Statistical analysis is applied to describe the basic features of the failure data for TBF and TTR at line level. A quantitative analysis of the failure data for the production line was obtained.

Total time	Minutes
Experiment	368,840
ΣTBF	325,103
ΣTTR	23,332
Changeovers of products	4,305
Trials	1,365
Interruptions (i.e. failures, changeovers and trials of products)	29,002
Scheduled interruptions	20,405

Notes: ΣTBF, sum time between failure; ΣTTR, sum time to repair

Table I. The experimental data for the croissant production line

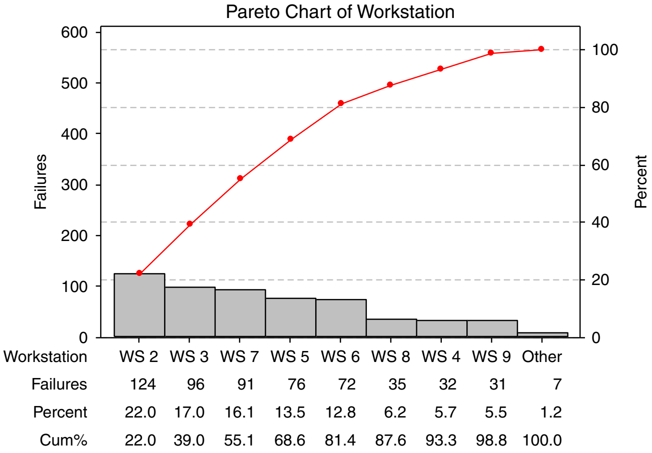

Figure 2. Pareto diagram of the failure data for each workstation of the croissant production line

The minimum and the maximum value of the sample, mean standard deviation (SD), coefficient of variation (CV), skewness and kurtosis of the failure data at machines and the entire line were extracted. Skewness is a measure of the degree of asymmetry of a distribution, while kurtosis is a measure of whether the data appear as peaks or are flat. A normal distribution will have kurtosis and skewness values equal to 0. Table II shows the descriptive statistics for the entire line of the croissant production line, and it is observed that: first, the mean TBF of failures is 584.7 min and drops to 457.7 min of the mean TBF due to scheduled and unscheduled interruptions for the production line. Second, on average every 2,868 min or 6 shifts there are changeovers of products on the line that last 36 min, whereas for 14,461 min or 40 shifts there are trials on the line that last about 60 min. Third, all the CVs are near to 1, meaning that there is low variability on failure data, and fourth, skewness and kurtosis are positives; therefore, clearly indicate that data of the croissant production line are not normally distributed.

Where *TBF Line Un* of equipment is defined as the time that elapses from the moment the equipment is turned on and starts operating after a failure (unscheduled interruptions), until the moment it goes down again and stops operation due to a new failure. *TTR Line Un* of failed equipment is defined as the time that elapses from the moment the equipment goes down and stops until the moment it goes up and starts operating again. Similarly, *TBF Line Sc/Un* of equipment is defined as the time that elapses from the moment the equipment is turned on and starts operating after a scheduled and unscheduled interruption (i.e. failure, changeovers, coffee breaks and trials), until the moment it goes down again and stops operation due to a new interruption. *TTR Line Sc/Un* of equipment is defined as the time that elapses from the moment the equipment goes down and stops due to scheduled and unscheduled interruption, until the moment it goes up and starts operating again. On the other hand, *TBF Changeovers* (or *TBF Trials*) of equipment is defined as the time that elapses from the moment the equipment starts operating after a changeover (or trials), until the moment it stops operation due to a new changeover (or trials). *TTR Changeovers* (or *TTR Trials*) of equipment is defined as the time that elapses from the moment the equipment stops due to a changeover (or trials), until the moment it starts operating again.

Moreover, reliability and maintainability jointly determine the inherent availability of a system. Thus, when an availability requirement is specified, there is a distinct possibility of trading-off between reliability and maintainability since, in the steady state, availability depends only on the ratio, α, that is referred to as maintenance time ratio (MIL-HDBK-338B 1998):

$$\alpha = \frac{mean\mathrm{TTR}}{mean\mathrm{TBF}}. \tag{5}$$

Table II. Descriptive statistics of the croissant production line based on scheduled and unscheduled interruptions

Variable	*n*	Mean	SD	CV	Min.	Max.	Skewness	Kurtosis
TBF Line Un	556	584.7	521.3	0.8916	8	3,715	2.21	6.12
TBF Changeovers	120	2,868	2,358	0.8223	90	11,850	1.29	1.25
TBF Trials	24	14,461	27,551	1.9051	465	131,360	3.7	15.09
TBF Line Sc/Un	698	457.6	379.4	0.8290	8	3,715	2.84	13.09
TTR Line Un	555	42.15	39.03	0.9259	3	320	2.96	11.86
TTR Changeovers	119	36.03	31.02	0.8610	2	300	5.56	44.32
TTR Trials	23	59.3	71.2	1.2004	10	300	2.66	6.87
TTR Line Sc/Un	697	41.61	39.21	0.9422	2	320	3.33	14.99

Notes: *TBF Line Un*, time between failure of the line with unscheduled interruptions; *TBF Line Sc/Un*, time between failure of the line with scheduled and unscheduled interruptions; *TTR Line Un*, time to repair of the line with unscheduled interruptions; *TTR Line Sc/Un*, time to repair of the line with scheduled and unscheduled interruptions

In Table III, the maintenance time ratio and inherent availability at machine and line level for the croissant production line were computed. The inherent availability (A_i) is calculated as the mean time between failure (*mean*TBF) divided by the mean time between failure plus the mean time to repair (*mean*TTR), or $A_i = mean\text{TBF}/(mean\text{TBF}+mean\text{TTR})$, or from Equation (5):

$$A_i = (1-\alpha)^{-1}.$$

The A_i related to equipment failure losses contained failures modes that stop the normal operation of the equipment and reduce its production rate. In addition, for the croissant production line when a random failure occurs, the failed machine stops and forces most of the line downstream of the failure to operate without processing, whereas the material of the line upstream may have to be scrapped due to quality deterioration during the stoppage. Thus, these losses are classified as time losses (reduced productivity), and quantity losses (occurrence of defective products) caused by equipment failure or breakdown. Therefore, the A and the Q, as well as the OEE of the line can be influenced.

From Table III, the following observations can be made (*Obj*1): first, the highest maintenance times ratios are at the forming (WS 2), the wrapping (WS 7) and the proofing (WS 3) with 0.016257, 0.015445 and 0.012457, respectively. Therefore, maintenance times of these workstations must also be reduced by adequate maintenance strategy (i.e. warehouse spare parts management, training program for technicians and operators, etc.), for increasing the inherent availability of the workstations. Second, the lowest maintenance time ratio is at the kneading (WS 1), the trays returned (WS 8) and the external failures (WS 9) with 0.000989, 0.002711 and 0.003063, respectively. Therefore, the maintenance of these workstations is satisfactory and no further action is needed. Third, the inherent availability of the line due to failures (unscheduled interruptions) is 93.67 percent, whereas the maintenance time ratio is 0.0721. Thus, the maintenance time ratio of the line is high and should be optimized with the adequate maintenance policy based on TPM principles.

The box plots are used to assess and compare the distributions of the data. It is a graphical method depicting the failure data through their quartile. The bottom of the box is the first quartile (Q1) or 25 percent of the failure data values which are less than or equal to this value. The middle of the data (median) represents half of the observations that are less than or equal to it. The top of the box is the third quartile (Q3) or 75 percent of the failure data values which are less than or equal to this value. Figure 3 shows the box plots with a mean connect line of the failure and repair data (unscheduled interruptions) at workstation level for the croissant production line. The quartiles, the median, the highest and the lowest values are presented for each workstation of the croissant production line. From Figure 3, the following observations can be made (*Obj*1): first, the minimum mean TBF is initially observed at the forming (WS 2), the robot lifting (WS 6) and the proofing (WS 3), meaning

Workstation	Failures	Mean TBF	Mean TTR	α	A_i
WS 1	7	49,734	49.2	0.000989	0.9992
WS 2	124	2,765	44.95	0.016257	0.9840
WS 3	96	3,585	44.66	0.012457	0.9878
WS 4	32	10,854	35.42	0.003263	0.9968
WS 5	76	4,552	33.06	0.007263	0.9929
WS 6	72	4,801	39.04	0.008132	0.9922
WS 7	91	3,772	58.26	0.015445	0.9851
WS 8	35	7,485	20.29	0.002711	0.9980
WS 9	31	11,207	34.33	0.003063	0.9970
Line	564	584.7	42.15	0.072088	0.9367

Table III.
Calculation of maintenance time ratio (α) and inherent availability (A_i) at workstation and line level for the croissant production line

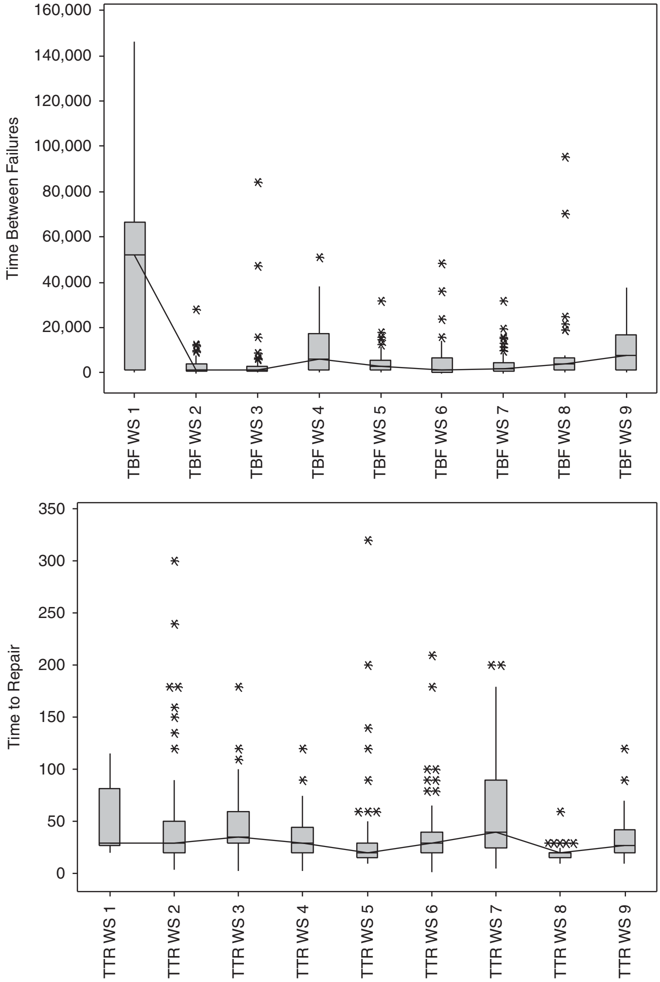

Figure 3.
Box plots for TBF and TTR (unscheduled interruptions) at workstation level for the croissant production line

that those workstations have low level of reliability. Second, the maximum mean TTR is at the wrapping (WS 7) and the proofing (WS 3). That is they have a high level of maintainability. Therefore, the managers/engineers of the production line must focus on forming (WS 2) and robot lifting (WS 6) in order to increase the reliability by the adequate maintenance policy. At the same time, the managers should improve the maintainability of the wrapping (WS 7) and the proofing (WS 3) by an appropriate training and education program for operators and the maintenance staff.

8. Calculation of OEE of croissant production line

The OEE consists of three components, where the first is the availability (*A*) that is an interpretation of design parameter for equipment and the reliability/maintainability trade-offs (Ebeling, 2008). The second component of the OEE calculation is the performance efficiency (*PE*) and the actual amount of production is measured. This component is affected by the speed of the production line and by mirror stoppages, i.e., adjustment losses.

The third component of the OEE calculation is the quality rate (*Q*), which is the proportion of good production to the total production volume. The *Q* is immediately related to the defective products of the line.

In order to start the OEE measurement process, operational performance data collection of the three OEE variables, availability, performance and quality, was carried out during a period of 15 months. The data required for the OEE measure were collected on a daily basis by the maintenance staff who are responsible for the continuous and correct operation of the croissant production line. The actual availability, performance efficiency and quality rate measures, together with the complete OEE figure for each working day, are shown in Figure 4.

Table IV presents the actual average OEE value calculated with the three components (*A*, *PE* and *Q*) for the entire period of operation. Moreover, the following observations can be made (*Obj*2): first, the availability of the line is 91.29 percent which is coincided with the target's availability (90 percent) of the production line. Second, the actual performance efficiency of the line is 83.09 percent, which abstains enough from the target (95 percent) of the production line. These losses are usually connected to the minor stoppages due to abnormalities on the forming (WS 2) or during the wrapping (WS 7). Third, the actual quality rate (98.88) approximates the target (99 percent) for the croissant line. The number of croissants rejected due to quality defects occurring during processing of the filling process (WS 5). Fourth, the overall OEE performance of the line is low (75.01 percent), considering

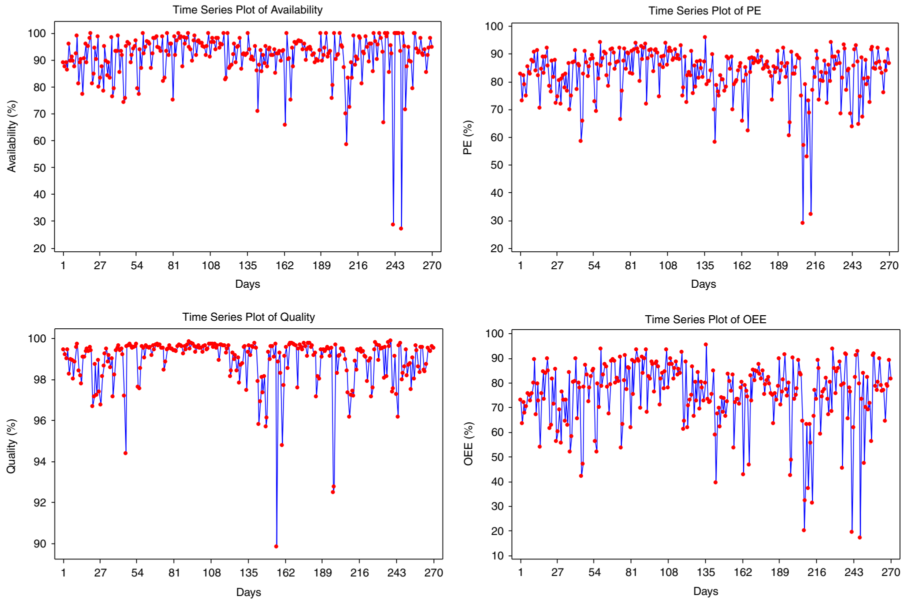

Figure 4.
The actual availability (*A*), performance efficiency (*PE*) and quality rate (*Q*) measures, together with the complete OEE figure for each working day for the croissant production line

Table IV.
The actual average of A, PE, Q, and OEE values that were calculated for the entire period of operation

%	*A*	*PE*	*Q*	OEE
World-class	90	95	99	84
Average	91.29	83.09	98.88	75.02
Difference	+1.29	−11.91	−0.12	−8.98

Notes: The actual average OEE value calculated with the three components (*A*, *PE* and *Q*) for the entire period of operation in comparison to the world-class target the target of an 84 percent benchmark as world-class performance (Zuashkiani *et al.*, 2011; Jonsson and Lesshammar, 1999). The main causes are speed losses, excessive breakdowns and high levels of defective products.

The croissant production line can be improved in two directions (*Obj*4). The first direction is to eliminate or restrict the scheduled interruptions that stand for 5.53 percent. These could be done by the adequate operation management for the line, i.e. scheduling production program of trials can be made outside the normal running time of the line. On the other hand, the changeovers may be programed at the beginning of the shift after a scheduled stop of the line, i.e. weekend, so that their time losses are reduced. Moreover, the operators must clean and prepare their machines before starting their machines again, so that rejection or rework may be reduced.

The second direction is to eliminate the unscheduled interruptions that consist of 6.33 percent due to failures that are downtime losses caused by unexpected breakdowns. This could be done with the proper maintenance strategy based on the TPM implementation program, in order to optimize equipment effectiveness. For instance, preventive maintenance (lubrication, adjustment of conveyor belts tension, bolt tightening, cleaning, inspection, etc.) of each machine for the croissant production line during the coffee break should be done by operators (or/and maintenance staff) to prevent breakdowns and faster reactions are necessary if a certain failure has been detected.

9. Conclusions

The main research findings of an automated croissant production line under real working conditions can be summarized as follows (*Obj*3):

(1) The overall OEE performance of the line is low (75.01 percent), considering the target of 84 percent. The main causes are speed and downtime losses. There is scope for further improvement of the croissant production line and especially into the component where a value of *PR* is much smaller than 95 percent.

(2) The inherent availability of the line is 93.67 percent due to unscheduled interruptions, whereas the maintenance time ratio is 0.0721. Thus, the maintenance time ratio of the line is high and should be optimized with the adequate maintenance policy.

(3) The croissant production line for 11.86 percent is under scheduled (5.53 percent, i.e. coffee breaks, changeovers of products and trials) and unscheduled (6.33 percent, i.e. failures) interruptions.

(4) The workstations forming (WS 2), proofing (WS 3) and wrapping (WS 7) stand for 55.1 percent of all the failures for the croissant production line.

(5) The highest maintenance time ratios are at the forming (WS 2), the wrapping (WS 7) and the proofing (WS 3). Therefore, the maintenance strategy of these workstations must be reviewed immediately.

(6) The minimum *mean*TBF are observed at the forming (WS 2) and then at the proofing (WS 3), whereas the maximum *mean*TTR are at the wrapping (WS 7) and the proofing (WS 3).

The paper is based on the assessment of failure data of an automated croissant production line under real working conditions. The line is representative in this section, and the failure data cover 15-month period. The operation of the line is not as expected; therefore, the components A, PE and Q as well as the OEE should be improved immediately. This could be done by eliminating or reducing the scheduled and the unscheduled interruptions (*Obj*4). The time of unscheduled interruptions should be reduced with the adequate maintenance strategy, i.e. TPM implementation program, parts replacement decisions, training and education programs for technicians/operators, spare parts requirement, etc. (Bon and Lim, 2011; Tsarouhas, 2007; Jain *et al.*, 2012; Kumar *et al.*, 2014; Phogat and Gupta, 2017; Wakjira and Singh, 2012). Moreover, in order to reclaim the coffee break, preventive maintenance (i.e. lubrication, adjustment of conveyor belts tension, bolt tightening, cleaning, inspection, etc.) of each machine for the line should be done by operators (or/and maintenance staff) to prevent breakdowns and faster reactions are necessary if a certain failure has been detected. On the other hand, the time of scheduled interruptions have to be eliminated. This could be done by properly scheduling production program, i.e. changeovers and trials of products on the production line are therefore made outside the normal running time of the line. The failure analysis conclusions can be very well applied to a variety of related bakery products and biscuits lines (apart from other croissant production lines) such as bread, cake, sandwich bread, panettone, biscuit, pizza, etc., because they have similar machinery and production processes. Therefore, a generalization of these line findings is feasible and applicable to the bakery and biscuits production lines of which the flow diagrams (processing) contain similar stages.

The role of academia is to bridge the gap between theory and practice in further developing and establishing the OEE as an improvement strategy. OEE has been used in industry in order to measure the performance of the equipment. OEE consists of three separate components (availability, performance and quality) where each aims at an aspect of the process that can be improved. Thus, the utilization of large quantity historical data was required in order to calculate the components. Due to the rare event of components, human error and economic restraints, it is difficult to obtain a large quantity of data from any particular plant for a long time period (Komal and Kumar, 2010). In addition, the companies are concentrated in the production process rather than to collect failure data. Also, some companies are introverted to publish their data due to the competition. Therefore, it is quite difficult to collect accurate and reliable failure data. In addition, a majority of the databases on which analyses rely are both outmoded and acquired under dissimilar performing and environmental conditions. Therefore, most articles are only absolute for cautiously particularized situations, which rarely happen.

On the other hand, there are significant gaps in the literature that supports OEE because the managers do not have easy access to the research models. Moreover, the models usually do not include all the costs associated with the production line (i.e. undelivered products due to unreliable equipment, the cost of poor operating conditions, cost of equipment-improvement activities, etc.) (McKone and Weiss, 1999). Therefore, the collaboration between the academic and industrial world must be established in both engineering and business schools. OEE has made a huge impact on the industries, but its impact on the academic community is limited. Thus, the creation of a space where the coexistence of the two is possible with huge, necessary benefits for both sides, i.e. for academic and industrial world.

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