Assessment of Overall Equipment Effectiveness (OEE) for marble manufacturing process: a case study

Arena S.*, Surracco M., Tilocca M.C.**, Pilloni M.T.***

** Department of Mechanical, Chemical and Materials Engineering, University of Cagliari, Via Marengo 2, 09123 – Cagliari – Italy (simonearena@unica.it, mteresa.pilloni@dimcm.unica.it)*

*** Department of Civil, Environmental Engineering and Architecture, University of Cagliari, Via Marengo 2, 09123 – Cagliari – Italy (surracco@unica.it, tilocca@unica.it)*

Abstract: Typical problems arising in the manufacturing industry, e.g. equipment breakdown, repair, and quality defects, have a great effect on the quality, cost and delivery time of goods. In this framework, the Overall Equipment Effectiveness (OEE) represents an important measure tool which involves the process of monitoring the availability, performance, and quality of manufacturing equipment and facilities. The performance evaluation measures of the three OEE factors give information about decisions and tasks which should be implemented to improve productivity and profitability. This paper investigates the efficiency loss of a marble manufacturing process aiming at identifying the root causes of bottlenecks operations to improve its system performance in terms of OEE and productivity. The OEE values are assessed over ten weeks, by considering four different processing cycles of the marble production: the block sawing process which consists in two sub-processes (slabs and tiles production), the polishing process and the resin treatment process. The types of potential equipment losses in OEE, as well as the factors availability, utilization, speed, quality, and planned stop time are identified for each processing cycle considered, to analyze how each OEE section impacts the overall OEE. From the empirical findings, operational performance efficiency losses are found to have the largest influence on OEE. Based on the results, improvement potentials and future tasks are identified to provide useful pieces of information for the decision-making when looking for the improvement of such a productivity indicator, including a preliminary economic assessment.

Keywords: OEE, improvement, efficiency losses, performance measurement, marble processing.

1.Introduction

In an increasingly and globally competitive industry, manufacturing sector is facing with the need of defining proper strategies to design and put into operation the production systems. In fact, in this context, one of the most challenging aspects is to increase knowledge of production development (Bellgran and Säfsten, 2010) to optimize productivity and to achieve quality targets aiming at both reducing production costs and meeting customer's expectation. To this end, the main purpose is to achieve a level of total efficiency to ensure reliable uninterrupted production (Wheelwright and Clark, 1992). Several factors influence the production process, such as stoppages due to machine failure, breakdowns, inefficient layout, non-conformance of goods, unskilled human resources among others. Thus, the basic idea is to reduce or eliminate these production outages. A widespread methodology used to improve production performance is Total Productive Maintenance (TPM), a lean tool introduced by Nakajima (Nakajima, 1989). In TPM, the Overall Equipment Effectiveness (OEE) is provided. It is a quantitative metric for measuring the productivity of an individual component in a factory, as equipment, machine, tool, process, etc. This metric is widely adopted by manufacturing companies to evaluate systems productivity, quality, performance and improvement thus, it represents a topic on which extended academic research has been conducted. Huang et al. (Huang et al., 2002) proposed an approach based on OEE to model the productivity of a leading glass production in terms of overall throughput effectiveness. Kombe et al. (Kombe et al., 2009) presented a method to model and evaluate the system efficiency based on the temporal and stochastic approach of OEE's component. Hedman et al. (Hedman, Subramaniyan and Almström, 2016) analyzed the critical factors that directly affect the accuracy of OEE for automatic measurement of manufacturing data. Tang (Tang, 2019) proposed a method to identify the bottlenecks of complex manufacturing systems by assessing the throughput losses included in OEE. Singh et al. (Singh *et al.*, 2013) developed a tool to automatically measure OEE of a machine. Kigsirisin et al. (Kigsirisin, Pussawiro and Noohawm, 2016) adopted TPM approach to water treatment plant by evaluating equipment effectiveness through OEE. Pereira et al. (Pereira *et al.*, 2019) applied OEE to the productivity improvement of an assembly line for brake cable processing in the automotive industry. Puvanasvaran et al. (Puvanasvaran, Mei and Alagendran, 2013) investigated OEE improvement by the implementation of time studies for autoclave processing in the aerospace industry. Muñoz-Villamizar et al. (Muñoz-Villamizar *et al.*, 2018) proposed a methodology for evaluating the effectiveness of urban freight transportation by using OEE. Andersson and Bellgran (Andersson and Bellgran, 2015) investigated the correlation between OEE and productivity to drive production improvements. Andras et al. (Andras *et al.*, 2006) using Monte Carlo simulation for measuring OEE in open-pit lignite mines production systems. Wang and Pan (Wang and Pan, 2011) developed an Automated Data Collection system to assess OEE losses in the semiconductor assembly industry. Hedman et al. (Hedman, Subramaniyan and Almström, 2016) analyzed the critical factors affecting OEE metrics for automatic measurement of manufacturing data. Vijaya Kumar et al. (Vijaya Kumar, Mani and Devraj, 2014) used OEE technique to improve the production planning and processes in an impeller manufacturing plant. Roda and Macchi (Roda and Macchi, 2019) studied the combination of OEE and reliability analysis to assess the performance of a buffered multi-state production system. Mwanza and Mbohwa (Mwanza and Mbohwa, 2015) presented the implementation of a Total Productive Maintenance model for a chemical manufacturing company. Miragliotta et al. (Miragliotta *et al.*, 2018) proposed a methodology to define and measure data productivity through the OEE framework. In (Guariente *et al.*, 2017) the authors proposed the implementation of autonomous maintenance to improve equipment availability in the automotive sector. Moreira et al. (Moreira *et al.*, 2018) used OEE metrics aiming at both improving productivity and reducing costs in printing industries. Jeong and Phillips (Jeong and Phillips, 2001) proposed to integrate the original definition of OEE (Nakajima, 1989) by including planned downtime such as scheduled maintenance, holidays and off-shifts as equipment losses, that should be considered in capital intense industry. Pinto et al. (Pinto *et al.*, 2019) implemented the performance indicators as MTBF, MTTR and OEE to continuous improvement actions in automotive sector.

In this paper, the authors investigate the efficiency loss of a marble manufacturing process aiming at improving its system performance. This analysis has been carried out through OEE evaluation by considering the different processing cycles to identify the root causes of bottlenecks operations of the whole production. In section 2, the Overall Equipment Efficiency metric is introduced. In section 3 a brief description of the marble manufacturing process considering the equipment involved is carried out. The results achieved and the possible improvements that can be made in this case study are finally discussed in section 4. Conclusion and future research are depicted in section 5.

2. Overall Equipment Efficiency (OEE)

In the ideal productive process, equipment should be operating at 100% of capacity and during 100% of time that means a process characterized by zero downtime, zero defects, and zero malfunctions. However, several efficiency losses exist generating a reduction of the production process efficiency. Whereby, a key aspect is the identification of these losses to quantify them. To this end, Overall Equipment Efficiency (OEE) is regarded as one of the most important metrics not only to monitor productivity and quality but also to provide strategic guidance for management decisions to create an improvement plan based on it. OEE is a quantitative metric that measures how well a manufacturing unit performs in relation to its full potential. It allows to identify sources of losses in production and to reduce both process variability and changeover times aiming at optimizing performance of the existing capacity and improving operator performance. These benefits of OEE help a company to maintain a competitive edge over its competitors as well as enhance production operations by making them more efficient and cost-effective. Throughout time, the original OEE indicator, developed by Nakajima (Nakajima, 1989), has been refined by meeting the different processing features of specific industrial application since factors affecting OEE could be slightly different as reported in (Jonsson and Lesshammar, 1999; Dal, Tugwell and Greatbanks, 2000; Ferrari *et al.*, 2001). However, in this paper, the reference definition developed by Nakajima is adopted in accordance with company management and specific application analyzed. It is defined as a product of three factors: availability, performance efficiency and quality, as reported in eq. (1):

$$OEE = Availability \times Performance \times Quality \quad (1)$$

$$Availability = \frac{Operating\ Time}{Loading\ Time} \quad (2)$$

$$Performance = \frac{Net\ Operating\ Time}{Operating\ Time} \quad (3)$$

$$Quality = \frac{Valuable\ Operating\ Time}{Net\ Operating\ Time} \quad (4)$$

where availability is defined as the ratio between the time the machine is available (operating time) and the time which is needed for production (loading time) as reported in eq. (2); performance takes into account when the machine is not run with full speed by comparing the net operating time and the operating time as reported in eq. (3); quality is the ratio between the valuable operating time and the net operating time as reported in eq. (4).

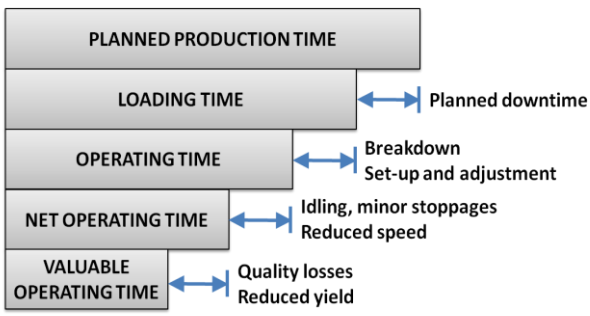

Figure 1: Definition of OEE based on Nakajima (Nakajima, 1989)

When achieved output is lower than expected, companies can find opportunities for improvement in all these factors aiming at maximizing process capabilities, fixing problems and improving productivity. OEE is based on three performance aspects and each of these elements is concerned with different losses. OEE loss categories can be further broken down into the six losses (Nakajima, 1989) as shown in Fig. 1.

3.Application of methodology in a marble facility

This work seeks to improve the effectiveness and productivity of a company located on the east-central coast of Sardinia (Italy) operating in the extraction and production of marble. The main goal is the identification of the different losses affecting the manufacturing processes to execute corrective actions aiming at reducing them. Thus, the first step consists in the classification of the productivity losses existing in the whole process. There are three principal causes of capacity losses in a production system:

- losses due to equipment malfunction: they depend on several possible causes, many of which are related to improper operations or poor maintenance among others.
- process losses: they depend on different use or treatment of work during production
- external losses: they are caused by conditions that are independent of the production and maintenance.

To this end, OEE is assessed over ten weeks, by considering four different processing cycles of the marble production:

- the block sawing process which consists in two sub-processes:
    - slabs production
    - tiles production
- the resin treatment process
- the polishing process.

A brief description of these processing cycles is provided in the following aiming at defining the context in which it can identify the causes of the time losses. All the equipment used in the different departments is considered part of a single production process.

3.1 Block sawing process: slabs production

After the excavation, the marble is transported in rough blocks to the processing plant. Once it reaches this plant, the first step is the block cutting process. The block is cut into slabs at previously determined thickness through a multiblade gang saw. The slabs are flat surface semi-finished products with unfinished edges that are sent to the successive resin treatment process or directly to the sales. In the slabs production department, the causes of capacity losses that occurred and registered in the selected period are described in the following:

Losses due to equipment malfunction: start-up, set-up, failures, maintenance (corrective and preventive), marble cutting blades breakage and replacement, clogging.

Process losses: unavailability of transferring trolley in/out (due to maintenance or failure), operators shortage, unavailability iron or wooden wedges for anchoring systems.

External losses: power outage, compressed air and water shortage for manufacturing processes, processing blocking of block sawing, limited marble storage areas, lack of raw materials (blocks).

3.2 Block sawing process: tiles production

The slabs are further cut into tiles of different dimensions by using bridge cutters. Generally, blocks characterized by defects or imperfections such as cracks or fissures, are used for tiles production. In the tiles production department, the causes of capacity losses that occurred and registered in the selected period are described in the following:

Losses due to equipment malfunction: start-up, set-up (gang saw), failures, maintenance (corrective and preventive), marble cutting discs or suction cup replacement, clogging (gang saw, milling machine, transferring trolley, rotating turntable).

Process losses: unavailability of operators for pallet handling, no pallet or no transferring trolley in/out available (due to maintenance or failure), operators shortage.

External losses: power outage, compressed air and water shortage for manufacturing processes, limited marble storage areas, lack of raw materials (blocks).

3.3 Resin treatment process

The first step consists in drying the slabs in the heating chambers. The second step is based on placing a fiberglass net-reinforcing on one face. In the third step, the epoxy resin is spread on the slabs surface filling the smallest existing cracks and micro-fissures. Then, the resin-treated slabs are dried by means of static catalysis process in vertical multi-decker kilns with hot-air circulating. In the resin treatment department, the causes of capacity losses that occurred and registered in the selected period are described in the following:

Losses due to equipment malfunction: start-up, set-up of heating chambers, failures, maintenance (corrective and preventive), suction cup replacement, clogging (heating chambers, automatic loading and unloading system, rotating turntable, conveyors).

Process losses: resin or fiberglass net unavailability, operators shortage (in particular for slabs transportation).

External losses: power outage, compressed air and water shortage for the manufacturing processes, limited marble storage areas, lack of raw materials (slabs).

3.4 Polishing process

The polishing process consists in removing all edges, scratches and roughness for getting smooth and shiny slab surfaces. This process involves several stages in which diamond pads characterized by different grit are used. In the polishing department, the causes of capacity losses that occurred and registered in the selected period are described in the following:

Losses due to equipment malfunction: start-up, set-up of polishing machine, failures, maintenance (corrective and preventive), suction cup or diamond pads replacement, clogging (polishing machine, automatic loading and unloading system, rotating turntable, conveyors).

Process losses: diamond pads or cellophane sheet unavailability, operator shortage.

External losses: power outage, compressed air and water shortage for the manufacturing processes, limited marble storage areas, lack of raw materials (slabs).

4.Results: OEE assessment

As stated before, the OEE values are assessed over ten weeks. The OEE identifies how effectively the whole system has been used compared to how its use could theoretically be maximized. Thus, additional causes of losses such as off-shifts, holidays and not-working weekends are taken into account. Therefore, in the considered period, the calendar time is 100800 minutes, equals for each process, while, the planned production time depends on the process, since it is defined as the period when the equipment is scheduled to run.

4.1 Slabs production department

In this department, the machines are scheduled to run for a full 12-h shift. In the selected period, the planned production time is 36000 min, while the planned downtime is assessed equal to three working days (due to holidays). Thus, the loading time is calculated as follows:

$$Planned\ Downtime = 3\ *(1\ shift * 12\ h * 60\ min/h) = \\ = 2160\ min$$

$$Loading\ Time = 36000 - 2160 = 33840\ min$$

OEE factors are calculated as follows according to eqs. (2), (3) and (4). During the considered period, no breakdown and no stop for machine set-up or adjustment occurred.

$$Availability = \frac{Operating\ Time}{Loading\ Time} =$$

$$= \left(\frac{33840}{33840}\right) * 100 = 100\ \%$$

This department consists in three gang saws and it has an overall cutting capacity of up to four blocks simultaneously. The slabs and the time needed to produce them depend on the height of each block. Thus, the Performance factor is achieved by considering the theoretical output defined as the output that the machine could have produced if it had operated at maximum speed during time and the actual output produced. Therefore, the slabs produced amounted to 6411 while the theoretical output is equal to 7909 items.

$$Performance = \frac{Net\ Operating\ Time}{Operating\ Time} =$$

$$= \frac{Actual\ Output}{Theoretical\ Output} = \frac{6411}{7909} * 100 = 81.1\ \%$$

This value is obtained due to minor stoppage and to equipment wear, in particular of the transferring trolley which generated speed losses. Quality factor is calculated by considering the ratio between the good units produced and the total production in the unit of time.

$$Quality = \frac{Valuable\ Operating\ Time}{Net\ Operating\ Time} =$$

$$= \frac{Good\ units - Rejected\ units}{Total\ production} =$$

$$= \frac{6411 - 315}{6411} * 100 = 95.1\ \%$$

Finally, the OEE for the slabs production process is obtained through eq. (1):

$$OEE = Availability \times Performance \times Quality =$$

$$= 100 * 81.1 * 95.1 = 76.8\ \%$$

4.2 Tiles production department

In this department, the machines are scheduled to run for two full 8-h shifts. In the selected period, the planned production time is 48000 min, while the planned downtime is assessed equal to three working days (due to holidays). Thus, the loading time is calculated as follows:

$$Planned\ Downtime = 3\ *(2\ shift * 8\ h * 60\ min/h) = \\ = 2880\ min$$

$$Loading\ Time = 48000 - 2880 = 45120\ min$$

During the considered period, no breakdown and no stop for machine set-up or adjustment occurred.

$$Availability = \left(\frac{45120}{45120}\right) * 100 = 100\ \%$$

For this process, the output is calculated as m^2 of tiles produced. Thus, the Performance value is:

$$Performance = \frac{21816\ [m^2\ of\ tiles\ produced]}{29844\ [m^2\ of\ theor. producible\ tiles]} \\ * 100 = 73.1\ \%$$

This value is obtained according to three factors: (a) minor stoppage and equipment wear of three different machines (the transferring trolley, the bridge crane and the circular saws); (b) under design production capacity; (c) raw products directly request from the market. Since tools to measure the scraps produced during tiles processing are not suitable, the value of Quality is established equal to 100%. Moreover, the scraps depend exclusively on the structural integrity and on the conformation of the blocks. Although the blocks can be characterized by irregular shapes, non-commercial measures or flaws, they are retrieved by means of tiles production of different sizes.

$$Quality = 100\ \%$$

Finally, the OEE for the tiles production process is:

$$OEE = Availability \times Performance \times Quality =$$

$$= 100 * 73.1 * 100 = 73.1\ \%$$

4.3 Resin treatment department

In the resin treatment department, the machines are scheduled to run for three full 8-h shifts. In the selected period, the planned production time is 72000 min, while the planned downtime is assessed equal to three working days (due to holidays). This department has been subjected to an additional planned downtime of 15 min. Thus, the loading time is calculated as follows:

$$Planned\ Downtime = 3 * (3\ shift * 8\ h * 60\ min/h) = \\ = 4320\ min$$

$$Loading\ Time = 72000 - 4320 - 15 = 67665\ min$$

In this process, general breakdowns, equipment failures and unplanned maintenance (4978 min), set-up and adjustment (460 min), occurred generating time losses equal to 5438 min. Thus the Availability factor is:

$$Availability = \left(\frac{67665 - 5438}{67665}\right) * 100 = 91.5\ \%$$

The theoretical capacity of resin treating is 90 slabs every 8 hours, corresponding to a theoretical output of 12690 slabs in the considered period. Because of reduced speed and minor stoppage, the actual output of 10817 slabs is achieved. Thus, the Performance value is:

$$Performance = \frac{10817}{12690} * 100 = 85.2\ \%$$

The scraps or rejected goods are 14 so, the Quality factor is equal to:

$$Quality = \frac{10817 - 14}{10817} * 100 = 99.9\ \%$$

Finally, the OEE for resin treatment department is:

$$OEE = Availability \times Performance \times Quality = \\ = 91.5 * 85.2 * 99.9 = 77.6\ \%$$

4.3 Polishing department

During the considered period, the polishing processing is not scheduled according to fixed shifts but these are planned in relation to quantity and type of goods required. Thus, the loading time is calculated as follows:

$$Planned\ Downtime = 68715\ min$$

$$Loading\ Time = 100800 - 68715 = 32085\ min$$

In this process, general breakdowns and equipment failures (1620 min), power outage and compressed air shortage (15 min), operators shortage (189 min), occurred generating time losses equal to 1824 min. Thus the Availability factor is:

$$Availability = \left(\frac{32085 - 1824}{32085}\right) * 100 = 94.3\ \%$$

The theoretical capacity of polishing processing is 12 or 13 slabs every hour (according to their dimensions) corresponding to a theoretical output of 6747 slabs in the ten-weeks considered. Because of reduced speed and minor stoppage occurred, the actual output of 5958 slabs is achieved. Thus, the Performance value is:

$$Performance = \frac{5958}{6747} * 100 = 88.3\ \%$$

The scraps or rejected goods are 26 so, the Quality factor is equal to:

$$Quality = \frac{5958 - 26}{5958} * 100 = 99.6\ \%$$

Finally, the OEE for the polishing department is:

$$OEE = Availability \times Performance \times Quality = \\ = 94.3 * 88.3 * 99.6 = 82.9\ \%$$

4.4 Discussion

Fig. 2 reports the value of Availability, Performance, Quality and OEE for the four departments analysed. It can be noticed, that the higher value of OEE is achieved for the polishing processing department. All these values are compared to the World Reference value, indicated by Nakajima (Nakajima, 1989), equal to 0.85. Since the values obtained in this study are lower than the Reference one, the objective is to identify which factor had a greater influence on OEE to implement possible improvement activities at the production process level.

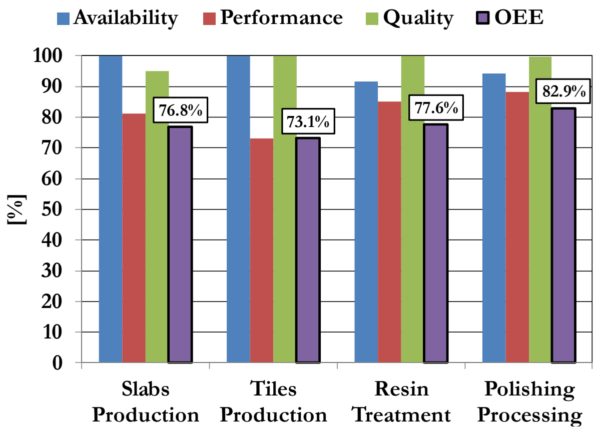

Figure 2: Availability, Performance, Quality and OEE valued for the different departments analysed.

For this reason, the OEE factors achieved are also compared to the Reference values (Nakajima, 1989) as reported in Table 1. As said, this comparison allows identifying possible improvement actions by focusing on the factor that is more away from reference. As can be observed, Performance is the factor that shows values far lower than the World Reference ones for all departments considered, while Quality shows lower values only for slabs production and polishing processing departments. In order to decrease the manufacturing losses which affect these factors, a productivity improvement process should be performed. The aim is to increase the output with the same or less amount of resources (input) or to produce the same amount of output with fewer resources.

Table 1: Comparison between World Reference values and Company's department values.

Factors	World Ref.	Slabs Prod.	Tiles Prod.	Resin Treat.	Polishing Proc.
Availability	90%	100%	100%	91.5%	94.3%
Performance	95%	81.1%	73.1%	85.2%	88.3%
Quality	99.9%	95.1%	100%	99.9%	99.6%

To this end, corrective actions are suggested to the company to reduce or eliminate manufacturing process failures. In the following, the suggested solutions are reported according to the different departments analysed. Due to company confidentiality policy, the economic analysis cannot be reported.

Slabs production department: the transferring trolley is the bottleneck of this manufacturing process. Indeed, the performance, capacity and functionality of this machine are limited due to wear and tear. This generates speed losses in the entire slab production process affecting the capacity of the three gang saws. A proper preventive maintenance program should be implemented to reduce or eliminate these losses. In accordance with company management, this solution would lead to a productivity increase equal to 500 slabs produced. In this case, a value of 87.4 % of Performance could be achieved, while OEE would be equal to 83.1 %. It seems clear that the obtained values are lower than the Reference values, but the proposed solution represents a practical and essential activity to keep the equipment in safe operable conditions, to increase productivity and to reduce wastes and breakdowns. The implementation of this solution would lead to a profit of about 72000 €/year. Finally, other solutions to improve Performance and Quality based on investing in new resources such as equipment, materials or manpower are not taken into account.

Tiles production department: in this case, only Performance is lower than the Reference value. As for the slabs production department, the solution proposed to reduce speed losses due to equipment wear is the implementation of preventive maintenance policy according to usage or time-based triggers. Another solution concerns the low production capacity of the machines used for tiles production. This loss could be reduced by means of the integration of a further production line, that consists in a gang saw and a milling machine. According to company management, the implementation of both solutions could improve Performance achieving a value equal to 87.1 %, nevertheless, it is still below the Reference value. On the other hand, the OEE (87.1 %) is higher than the Reference one (85 %).

Resin treatment department: Availability and Performance values are lower than the Reference ones. As said before, during the considered period, two different factors affect Availability: equipment breakdowns resulting in unplanned maintenance and operators shortage. Since several breakdowns occurred have generated significant downtime losses, a preventive maintenance policy should be implemented taking into account the equipment history. It includes periodic and regular inspection based on cleaning, adjustment, replacement and repairs aiming at increasing life components and reducing failure and costs. Concerning the operators' shortage, it is important to develop a strategic workforce scheduling aiming at meeting the operational demands of the production process. Performance is widely influenced by the low production capacity of equipment such as the bridge crane and the heating chamber. Indeed, the amount of items that can be worked is limited by the use of a single bridge crane, as well as the heating chamber is undersized for the actual production of the company. According to company management, the implementation of these proposed solutions could improve Availability and Performance achieving a value equal to 95.5 % and 89.2 % respectively. Consequently, OEE value is 85.1 %, slightly higher than the Reference one.

Polishing department: in this department, the downtime losses are generated by breakdowns and equipment failures, power outage and compressed air shortage, operators shortage. Also in this case, a preventive maintenance program and proper workforce scheduling could improve Availability. Concerning Performance, the low production capacity greatly influences the polishing process. This generates low volume of items that are processed related to the desired volume. To this end, the possible modification of the department layout, as well as its modernization, are currently being investigated by company management. Thus, no hypothesis or economic analysis on the implementation of the proposed solution is reported for this department.

5.Conclusions

This paper analysed the system performance of a marble manufacturing process by assessing the Overall Equipment Effectiveness (OEE) over ten weeks. The study is focused on the identification of the efficiency losses of four different processing cycles of the marble production: the slabs process production, the tiles process production, the resin treatment process and the polishing process. The results show that the OEE achieved for the different processes is lower than the World References value for manufacturing processing. Indeed, several losses are detected: (a) the current maintenance generates numerous failures, prolonged downtime, less availability and reliability of the different equipment; (b) operators shortage; (c) under design capacity which generates low volume of processed items related to the desired volume. All these losses widely affect productivity. These findings will be of use to company management aiming at improving OEE of the entire manufacturing line. To this end, improvement potentials and future tasks are identified to provide useful solutions for the decision-making process. A great benefit could be achieved by the implementation of a proper preventive maintenance policy to reduce unexpected failure, downtime and costs with a consequent improvement of profitability. Thus, a strategy for maintaining and improving the integrity of production and quality of the entire system (equipment, processes and operators) based on planning, control and supervision of it in order to add value to the company. Moreover, a significant improvement could be obtained by modernizing the company's organization structure by taking into account its resources: this change involves the development of both a strategic workforce scheduling and an implementation of automation processes and equipment.

Acknowledgments

The authors would like to acknowledge the S.I.M.G. S.r.l. who provided the opportunity to conduct this research.

The research would not have been possible without the extensive participation and collaboration of Dr. Pala and the involved company employees.

References

Andersson, C. and Bellgran, M. (2015) 'On the complexity of using performance measures: Enhancing sustained production improvement capability by combining OEE and productivity', *Journal of Manufacturing Systems*. The Society of Manufacturing Engineers, 35, pp. 144–154.

Andras, I. *et al.* (2006) 'Research Regarding the Oee (Overall Equipment Effectiveness) Assessment of the Coal Open Pit Mines Production System', *Annals of the University of Petroșani, Mechanical Engineering*, 8, pp. 139–146.

Bellgran, M. and Säfsten, K. (2010) *Production development: design and operation of pro-duction systems*. Edited by Springer Verlag. London.

Dal, B., Tugwell, P. and Greatbanks, R. (2000) 'Overall equipment effectiveness as a measure of operational improvement – A practical analysis', *International Journal of Operations & Production Management*, 20(12), pp. 1488–1502.

Ferrari, E. *et al.* (2001) 'TPM: a total approach for industrial maintenance question', in *Proceedings of 7th International Conference in Reliability and Quality in Design – ISSAT01*. Washington DC, pp. 262–268.

Guariente, P. *et al.* (2017) 'Implementing autonomous maintenance in an automotive components manufacturer', *Procedia Manufacturing*. Elsevier B.V., 13, pp. 1128–1134.

Hedman, R., Subramaniyan, M. and Almström, P. (2016) 'Analysis of Critical Factors for Automatic Measurement of OEE', *Procedia CIRP*, 57, pp. 128–133.

Huang, S. H. *et al.* (2002) 'Manufacturing system modeling for productivity improvement', *Journal of Manufacturing Systems*, 21(4), pp. 249–259.

Jeong, K.-Y. and Phillips, D. T. (2001) 'Operational efficiency and effectiveness measurement', *International Journal of Operations & Production Management*, 21(11), pp. 1404–1416.

Jonsson, P. and Lesshammar, M. (1999) 'Evaluation and improvement of manufacturing performance measurement systems - the role of OEE', *Int. J. Oper. Prod. Manage*, 19(1), pp. 55–78.

Kigsirisin, S., Pussawiro, S. and Noohawm, O. (2016) 'Approach for Total Productive Maintenance Evaluation in Water Productivity: A Case Study at Mahasawat Water Treatment Plant', *Procedia Engineering*, 154, pp. 260–267.

Kombe, T. *et al.* (2009) 'Global efficiency assessment based on component composition of OEE using AltaRica Data-Flow language', *IFAC Proceedings Volumes (IFAC-PapersOnline)*. IFAC, 42(4 Part 1), pp. 246–251.

Miragliotta, G. *et al.* (2018) 'Data driven management in Industry 4.0: a method to measure Data Productivity', *IFAC-PapersOnLine*. Elsevier B.V., 51(11), pp. 19–24.

Moreira, A. *et al.* (2018) 'Cost reduction and quality improvements in the printing industry', *Procedia Manufacturing*. Elsevier B.V., 17, pp. 623–630.

Muñoz-Villamizar, A. *et al.* (2018) 'Using OEE to evaluate the effectiveness of urban freight transportation systems: A case study', *International Journal of Production Economics*, 197, pp. 232–242.

Mwanza, B. G. and Mbohwa, C. (2015) 'Design of a Total Productive Maintenance Model for Effective Implementation: Case Study of a Chemical Manufacturing Company', *Procedia Manufacturing*. Elsevier B.V., 4, pp. 461–470.

Nakajima, S. (1989) *Introduction to total productive maintenance*. Edited by Productivity Press.

Pereira, J. *et al.* (2019) 'Application of the A3 Methodology for the Improvement of an Assembly Line', *Procedia Manufacturing*. Elsevier B.V., 38(2019), pp. 745–754.

Pinto, G. F. L. *et al.* (2019) 'Continuous improvement in maintenance: a case study in the automotive industry involving Lean tools', *Procedia Manufacturing*. Elsevier B.V., 38(2019), pp. 1582–1591.

Puvanasvaran, A. P., Mei, C. Z. and Alagendran, V. A. (2013) 'Overall equipment efficiency improvement using time study in an aerospace industry', *Procedia Engineering*. Elsevier B.V., 68, pp. 271–277.

Roda, I. and Macchi, M. (2019) 'Factory-level performance evaluation of buffered multi-state production systems', *Journal of Manufacturing Systems*. Elsevier, 50(November 2018), pp. 226–235.

Singh, R. *et al.* (2013) 'Overall equipment effectiveness (OEE) calculation - Automation through hardware & software development', *Procedia Engineering*, 51, pp. 579–584.

Tang, H. (2019) 'A new method of bottleneck analysis for manufacturing systems', *Manufacturing Letters*. Society of Manufacturing Engineers (SME), 19, pp. 21–24.

Vijaya Kumar, S., Mani, V. G. S. and Devraj, N. (2014) 'Production Planning and Process Improvement in an Impeller Manufacturing Using Scheduling and OEE Techniques', *Procedia Materials Science*, 5, pp. 1710–1715.

Wang, T. Y. and Pan, H. C. (2011) 'Improving the OEE and UPH data quality by Automated Data Collection for the semiconductor assembly industry', *Expert Systems with Applications*. Elsevier Ltd, 38(5), pp. 5764–5773.

Wheelwright, S. C. and Clark, K. B. (1992) *Revolutionizing Product Development: Quantum Leaps in Speed, Efficiency and Quality*. Edited by Free Press. New York, NY, USA.