Received 15 September 2022, accepted 22 September 2022, date of publication 3 October 2022, date of current version 12 October 2022.
Digital Object Identifier 10.1109/ACCESS.2022.3211266

RESEARCH ARTICLE

Application of the Overall Equipment Effectiveness to a Service Company

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This work was supported in part by SIRTI S.p.A.

This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the Department of Security and Data Management of the Sirti S.p.A. Company in accordance with the Italian and European General Data Protection Regulation.

ABSTRACT Competitiveness has reached outstanding levels in every marketplace sector. The Overall Equipment Effectiveness (*OEE*) framework has gained increasing interest in different contexts as a leading measure for improving production. The application of the *OEE* as a driver of improvement is an extensively covered topic in scientific literature. However, the existing research mainly focuses on case studies showing the obtained results on specific applications, typically in the manufacturing domain. This paper proposes the adaptation of the *OEE* framework for its application to service companies. The obtainable results and the involved possible errors in the use of the framework are addressed. We show the benefits of the proposed framework for allowing a meaningful comparison of employees performing different types of activities. Inefficiencies can be identified and classified by associating them with causes. Methods, procedures, and territorial aspects are related in general to the company organization. The application of the *OEE* transforms the measures from targets to drivers of improvements by identifying the areas of loss in the process. The proposed framework is demonstrated in a case study consisting of a service company operating in the telecommunication field. The evaluation has been done over a time-span of 12 months, addressing the behavior of 952 employees. The analysis allows producing results that are useful to assess the behavior of the company. In particular, we can distinguish the causes of losses either related to the employees or the ones related to the company. Different types of losses are quantified, and this information can be used to optimize the various aspects in detail. The assessment of the losses enables the comparison of the performance among different areas and different employees.

INDEX TERMS Asset management, business data processing, business intelligence, business process management, data analysis, digital transformation, overall equipment effectiveness, production management, resource management, service engineering, total productive maintenance.

I. INTRODUCTION

The focus on performance measurement considers the company as an economic organization aimed at measuring the performance of its production processes. Control and measurement systems have grown in importance, becoming decisive in the creation and maintenance of the company's competitive advantage. "These tools do not aim to accurately measure the economic reality, but rather the processes that, if properly designed and implemented, can positively influence the behavior of individuals and groups, directing them to the achievement of institutional purposes" [1]. Performance measures would result in a useless application of measurement techniques if company management did not use them to direct the organization's efforts to achieve the set objectives. Currently, the measurement of company performance is a consolidated practice: an effective measurement system "allows decisions to be made and actions to be taken as it

The associate editor coordinating the review of this manuscript and approving it for publication was Xianzhi Wang.

is able to quantify the efficiency and effectiveness of past actions through the acquisition, collection, the selection, analysis, interpretation and dissemination of adequate data'' [2].

Optimization has become one fundamental aspect to address. However, this has to be pursued with a methodical approach. To be able to maintain and develop their ability to compete on a global market, manufacturing companies need to develop innovative and high-quality products in short lead time. Robust and flexible production systems are the best preconditions for operational excellence [3].

The Overall Equipment Effectiveness (*OEE*) has gained increasing interest in different contexts as a leading measure for improving production. The application of the *OEE* as a driver of improvement is an extensively covered topic in scientific literature. The *OEE* is a framework, intended as ''a network of interlinked concepts that together provide a comprehensive understanding of a phenomenon or phenomena'' [4], introduced by Nakajima in 1988 [5]. It is part of the so-called Total Productive Maintenance (*TPM*). The *TPM*, in turn, has been invented in Japan in the 1970s to increase the equipment effectiveness focusing on maintenance. The *OEE* is the measure of the equipment productivity in a manufacturing system. Essentially, it is a productivity ratio between value added time and the total time available to produce. The *OEE* is built upon the concepts of Availability (A), Performance (P) and Quality (Q), which measure the impact of the various types of losses that reduce the actual total time available to produce. The goal of the *TPM* is to increase the value of the *OEE*. This framework is widely accepted and implemented by industries, mainly in the manufacturing domain.

There is an extended literature on the *OEE*. However, the existing research mainly focuses on case studies showing the obtained results on specific cases, or the customization of the *OEE* to such specific use cases. On the other hand, several case studies on manufacturing industries discuss the application of the *OEE* as a performance target. The application of the *OEE* to service companies is much less addressed in the scientific literature. The *OEE* framework has been adapted from its original purpose, which is the assessment of the productions of goods in an industry, to assess the performance of the employees of a service company [6].

In our research, we have identified a lack of literature on understanding the holistic view of the *OEE* framework. The comprehension of phenomena can not be explained solely by its components taken individually, but it is necessary to observe and analyze the functional composition of all their parts. The *OEE* was conceived with the precise goal of creating a structure in which the indicators are correlated with each other, where the variation of one aspect acts on the others according to a clear logic. We believe that a deep understanding of the relationships among the elements composing the *OEE*, and the correct interpretation of their variation, may be useful as a guide for a practical application and, additionally, to allow the identification of potential areas of improvement.

This paper introduces an adaptation of the *OEE* for its application to a service company. The aim of the work is not limited to address the answer of the typical question in a company with thousands of employees who carry out a stand-alone job, which is *"How is it possible to observe and calculate the efficiency?"*. Indeed, our work aims at more insightful questions, which are the following:

Q1 How can the efficiency bottlenecks be identified?
Q2 What is the impact of territorial peculiarities on the efficiency?
Q3 How can different employees working in heterogeneous territories be compared?
Q4 Which factors can be leveraged to obtain an holistic view of the efficiency?
Q5 How could typical errors in the use of *OEE* be mitigated?

Regarding question **Q5**, the main typical error in the application of the *OEE*, which is addressed in this work, is the use of expected values for the calculations that are too large, leading to overestimation of the productivity.

We show the benefits of the proposed framework to allow a meaningful comparison of employees performing different activities. Inefficiencies can be identified and classified by associating them with causes. Such causes can be related to methods, persons and territorial aspects. The application of the *OEE* transforms the measures from targets to drivers of improvements by identifying the areas of loss in the process.

This paper aims at demonstrating the application of the *OEE* in the assessment of the performance of a service company operating in the telecommunication's field. The evaluation will be done over a timespan of 12 months, addressing the behavior of 952 employees.

The paper is organized as follows. Section II overviews the related works, starting from the Toyota Production System (*TPS*), and illustrating the pillars that allow to establish the relationship between *TPM* and *OEE*. Concepts of the traditional *OEE* are introduced in Section VI. A model for the losses is presented in Section VII, while Section V describes the adaptation of the *OEE* framework to a service company. Section VI discusses the losses affecting the service company. The characteristics of the case study are presented in Section VII, while an analysis of the territorial performance of the company is provided in Section VIII. Section IX discusses the results obtained in the application of the proposed framework to the considered case study. Section X discusses some limitations of the proposed framework. Section XI concludes the paper, providing answers to the questions formulated in the introduction section.

II. RELATED WORKS

The history of the Overall Equipment Effectiveness (*OEE*) begins in 1980, when Nakajima proposed the concept of Total Productive Maintenance (*TPM*) [5]. *TPM* is proposed as the production system that aims at optimizing production effectiveness by identifying and eliminating losses of both equipment and efficiency across the whole product life cycle.

TPM became highly regarded in the manufacturing industry in the 1980s. *OEE* is a tool introduced by Nakajima in [5] to measure the progress made in applying the *TPM*.

In [7], the authors state that, typically, *OEE* is implemented to measure resource utilization in a plant. In companies with multiple plants, it allows for comparison of facilities. However, the *OEE*, implemented as a measure of efficiency, later becomes the tool to improve effectiveness through the identification and elimination of losses. In fact, the *OEE* should be used as a driver for improvement, not as a performance measure to compare production units, as stated by Kennedy in [8]. In [9], the authors discuss how the *OEE* is traditionally used by companies as an operational measure but rarely as a driver of productivity enhancement actions. The *OEE* can be used, in combination with productivity measures, as a driver for improvements to the process in the manufacturing industry. The paper presents a set of Key Performance Indicators (KPIs) to guide improvements that should be monitored before, during and after the improvement project, to capture capacity improvements. Other factors that impact the success of the project are the software automation in the calculation of KPIs and the active involvement of the personnel.

Through the case study based on an automotive company, [10] brings some conclusions on the misuse of the *OEE*. This is a consequence of a misunderstanding about the concept of the index. The authors raise a doubt regarding the correct cycle time. In particular, they wonder whether it should be the ''technical'' cycle time or the ''planned'' cycle time. The authors state that the use of technical time is a mistake. However, using the planned cycle time leads to an overestimation of performance and *OEE*. Another misuse of the *OEE* value is its use for bottleneck identification: the *OEE* value alone does not help in identifying the sources of problems.

Back in 1995, Peter De Groote anticipated how the future will increasingly focus on the effectiveness of the company through changes in management models [11]. This requires re-engineering the organization and a radical change in staff behavior. However, quantifiable indicators of economic and technical performance are necessary. In [11], the *OEE* is presented as the product of 3 indicators: Availability, Speed (instead of Performance) and Quality.

The results in [12] suggest changing focus and using a comprehensive loss model and highlighting the problem of data collection. According to the study, at the beginning of its application the *OEE* is relatively low, with values below 55% even if the company is already familiar with the production process. In [13], Kotze argues that an OEE under 50% is realistic. On the other hand, [14] reports that an *OEE* target of around 85% is not uncommon.

The importance of an accurate estimation of the use of equipment to identify hidden losses of time and planning in the correct data collection is reiterated in [15]. The paper proposes a novel classification scheme of losses for a new interpretation of the *OEE*.

More and more companies are looking for a customized maintenance concept. The framework introduced in [16] presents some guidelines for developing this concept. The authors stress the importance of incorporating all information available in the company: the experience of the maintainers and the collected data. How to make each operator or technician to adopt the *TPM* plays a crucial role.

A. APPLICATIONS OF THE OEE

There is a large number of applications of the *OEE* reported in the scientific literature.

An adaptation of the *OEE* to the transport domain is presented in [17]. The framework applied in that context is extendable to other cases, such as third party logistics or large companies with a high number of daily routes and delivery customers.

In their case study [18], the authors propose a new methodology for the evaluation of the effectiveness of urban freight transport systems using the *OEE* metric. Urban transport of goods is a small part of the shipping time, but it can account for up to 28% of the shipping cost. The aim is to optimize *OEE* metrics and the profitability of a transportation system by reducing overall costs and increasing revenues.

The experience in applying optimization methods, including the *OEE*, to Small and Medium-Sized Enterprises (SMEs) is described in [19]. Critical success factors are identified that make achieving results within SMEs more problematic. Factors such as shortages in funding, leadership and workforce training can negatively affect the general performance of the company.

The literature on maritime port performance presents sophisticated analyses using parametric and non-parametric models, but in many cases these results suffer from the contamination of exogenous effects in efficiency calculations. A methodology is proposed to separate manageable and unmanageable factors in [20]. A set of performance indicators is presented to evaluate the efficiency of the terminal based on the distribution of the *OEE*, which allows the definition of achievable efficiency and performance objectives.

In [21], the authors describe a technology to accurately measure the *OEE* in real-time to support the latest advancements in the context of Industry 4.0.

B. EXTENSIONS OF THE OEE

Over time, the *OEE* was adapted to several different and peculiar contexts. As a result, new indicators have been formulated, based on the original *OEE*.

From the analysis of evolution and application in industries, the authors of [22] infer that the *OEE* is a valuable measure. The paper provides information on lost time and lost production. The paper provides a comparison of different reformulations of the *OEE*, namely Total Equipment Effectiveness Performance (TEEP) [23], Production Equipment Effectiveness (PEE) [24], Operational Event (*OPE*), Overall Asset Effectiveness (OAE) and Overall Factory Effectiveness (OFE). However, in low-volume farms, the *OEE* and its measures are not very efficient, since the unscheduled production time is too high. Moreover, the accuracy of the data for the *OEE* is very important. Without accurate data, measuring *OEE* can easily lead to a lack of credibility. Therefore, it is important to invest time and money to improve data collection and automatize it.

Some drawbacks of *OEE* are presented and discussed in [25]. One such limitation is that *OEE* can only measure the efficiency of individual equipment. However, machines are typically not isolated but work together in a production line. To address this problem, a new efficiency metric called Overall Equipment Effectiveness of a Manufacturing Line (OEEML) is presented and applied to an industrial case. The paper concludes that further research is needed to integrate OEEML with other metrics to monitor equipment operating costs and inefficiencies in line costs.

The Overall Environmental Equipment Effectiveness (OEEE) metric is presented in [26] as a possible green and lean production solution. The conclusions are that the OEEE allows business decisions to include sustainability aspects and demonstrates the compatibility between green and lean manufacturing. This new metric should allow companies to include sustainability as a criterion in business decision making.

The Overall Resource Effectiveness (ORE) metric is investigated, through two case studies, in the measurement of the effectiveness of production [27]. The ORE allows monitoring of changes in process costs, changes in material costs, and material efficiency. In certain processes, ORE is more complete and achievable with respect to the measurement obtained by the traditional *OEE*.

The Overall Manufacturing Performance (OMP) is presented in [28] as a metric that takes into consideration several factors for the evaluation. The OMP is evaluated at the global system level across 3 case studies. A framework for the evaluation of the OMP is developed, and the *OEE* is integrated into the overall measurement system. The authors show that the *OEE* is lacking some key aspects w.r.t. the OMP, but it is a useful part of a global measurement system.

In their article [29], the authors discuss a production system based on a continuous production line. In this situation, it is necessary to focus not only on the performance of a single machine, but also on the performance of the line. *OEE* is sufficient to improve the effectiveness of individual production equipment. In the paper, the Overall Line Effectiveness (OLE) is presented as a tool that provides an appropriate solution for monitoring and improving the production line.

The effectiveness of *OEE* is reiterated in [30] for measuring the productivity of individual production equipment. However, the need to improve the performance of the whole process requires different solutions. The effectiveness of the OLE is applied to a case study, and a new approach is proposed to evaluate the quality rate of the production system using the Principal Component Analysis (PCA).

A new indicator called Overall Task Effectiveness (OTE) has been introduced in [31] as a practical method to analyze and evaluate the main causes of loss in a production environment characterized by complex final products. The OTE supports Lean and Six Sigma methodologies [32] and applies them to companies. The new metric and the losses were verified by studying a manual station for the assembly of railway wagons. The results demonstrate that the OTE can help the analyst in both defining and meeting the target performance in terms of the time required to complete the expected tasks.

A methodology is proposed in [33] for productivity improvement. A complex production system can be treated as the combination of simple subsystems. These are the combination of Production Process Units (UPP), which are individual units used in the manufacturing lines. The model uses different production metrics, including *OEE*, Overall Throughput Effectiveness (OThE), and Cycle Time Effectiveness (CTE), and applies the theory of constraints.

In [34], the authors present the Overall Equipment Productivity (OEP) metric as a KPI in the semiconductor industry. The metric is based on the *OEE* and it is used to determine the cycle timeshare of the total process time.

III. CONCEPTS FROM THE TRADITIONAL *OEE*

According to Nakajima [5], the *OEE* is formulated in terms of 3 factors, expressed as percentages: Availability (A), Performance (P) and Quality (Q).

Mathematically, the *OEE* is calculated by Eq. (1):

$$OEE = A \cdot P \cdot Q \qquad (1)$$

Dunn [35] defines the 3 mentioned factors as answers to the following questions:

- Availability: Is the machine running or not?
- Performance: How fast is the machine running?
- Quality: How many produced items satisfied the requirements?

To motivate this statement, we analyze the elements that compose the *OEE*. Based on the concepts proposed by [5], we define the following terms.

Definition 1: The Total Time Available (TT) is the total working time during the day, including scheduled stops during which no production is performed (e.g., meetings, formation, etc.).

Definition 2: The Expected Cycle Time (ECT) is the necessary theoretical time for the production of a compliant product.

The *ECT* is also known as *Cycle Time*, *Theoretical Time* or *Standard Time*. The *ECT* is a parameter that needs to be correctly quantified for an accurate evaluation of the *OEE*.

Definition 3: The Valuable Operating Time (VOT) is the theoretical time taken by the operating unit to produce *added value*.

In the literature, the value of *VOT* is calculated as the number of compliant products multiplicated by the *ECT* [8].

Definition 4: The Total Planned Production Time (PPT) is the real total time to carry out activities that create value.

The *VOT* can also be seen as the fraction of the *PPT* in which the unit operates in optimal conditions [25].

The classic formula of efficiency, and therefore the simple form of the OEE, is expressed by Eq. (2) as a ratio between VOT and PPT [8]:

$$OEE = \frac{VOT}{PPT} \tag{2}$$

In this form, the OEE does not allow to identify the bottlenecks, i.e., the causes of the efficiency losses, and thus does not help in addressing the questions that are posed in the introduction of this paper, with special reference to question **Q1**.

IV. MODEL OF LOSSES

The evaluation of the OEE is strictly related to the definition and the evaluation of the causes of losses that can happen in the company. Nakajima [5] classifies the losses into 6 categories, the so-called *Six Big Losses*.

Definition 5: The six Big Losses are defined as follows:

1) Equipment Failure and Breakdown (BL_{EFB}): The time loss caused by equipment failure or breakdown.
2) Set-ups and Adjustments ($BL_{S\&A}$): The time loss occurring when a production unit changes the type of product, and thus set-ups and adjustments are required to start the new production.
3) Idling and Minor Stoppages (BL_{IMS}): During production minor stops can occur; these events are considered to be difficult or too expensive to record. This loss includes the time of all the activities that can not be tracked.
4) Reduced Speed (BL_{RS}): The extra time spent on production compared to the ECT. It is a loss of speed in production, which applies to both compliant and not compliant products.
5) Process Defects (BL_{PD}): The sum of the ECTs of the not compliant parts due to defects. Defective products are not compliant, and may be reworked or rejected.
6) Reduce Yield (BL_{RY}): The time required to produce rejected parts due to changeovers or incorrect settings that may take some time to achieve stable production.

The 3 factors that compose the OEE, namely A, P and Q, is a measure of such losses [28]. In particular, the Availability measures the downtime losses due to breakdowns (BL_{EFB}) and set-ups or adjustments ($BL_{S\&A}$). The Performance measures the speed losses due to minor stoppages (BL_{IMS}) and reduced speed (BL_{RS}), while the Quality measures the losses due to process defects (BL_{PD}) and reduced yield (BL_{RY}).

As a result, the improvement of the OEE is related to the production of more compliant products (improving Q), as fast as possible (improving P), and with fewer stop times (improving A) [18].

The six big losses can be grouped into 3 families, according to the following definition.

Definition 6: The 3 families of losses are defined as follows:

1) Down Time Family Losses (FL_{DW}) – Includes the losses BL_{EFB} and $BL_{S\&A}$; it affects the Availability.
2) Speed Family Losses (FL_{SP}) – Includes the losses BL_{IMS} and BL_{RS}; it affects the Performance.
3) Defect Family Losses (FL_{DF}) – Includes the losses BL_{PD} and BL_{RY}; it affects the Quality.

The definition of the losses results in the following relationships:

$$FL_{DW} = BL_{EFB} + BL_{S\&A} \tag{3}$$
$$FL_{SP} = BL_{IMS} + BL_{RS} \tag{4}$$
$$FL_{DF} = BL_{PD} + BL_{RY} \tag{5}$$

Eq. (6) captures the relationship between the six losses, the time that generates *added value* (VOT) and the PPT:

$$PPT = VOT + (BL_{EFB} + BL_{S\&A}) + (BL_{IMS} + BL_{RS}) + (BL_{PD} + BL_{RY}) \tag{6}$$

Eq. (6) could be rewritten as follows (Eq. (7)), by combining Eq. (3), Eq. (4) and Eq. (5):

$$PPT = VOT + (FL_{DW} + FL_{SP} + FL_{DF}) \tag{7}$$

Dividing Eq. (7) by PPT, the formulation of the OEE becomes:

$$OEE = 1 - \frac{(FL_{DW} + FL_{SP} + FL_{DF})}{PPT} \tag{8}$$

Eq. (8) highlights that the OEE is equal to 100% minus the percentage impact of the losses on the PPT.

As introduced in Eq. (1), Nakajima [5] defines the OEE as a product of the 3 rate percentages factors: A, P and Q. On the other hand, Eq. (8) shows how the OEE is directly affected by the six losses.

To show the relationship among the 3 factors and the losses, we introduce the following definitions.

Definition 7: The Operating Time (OT) is the available time to perform the production of goods. It can be calculated as follows:

$$OT = PPT - FL_{DW} \tag{9}$$

Given the relationship between the family losses and the losses, Eq. (9) can also be written as

$$OT = PPT - (BL_{EFB} + BL_{S\&A}) \tag{10}$$

Definition 8: The Net Operating Time (NOT) is the net worked time (OT) without the losses caused by slow production (BL_{RS}) or short stops difficult to track (BL_{IMS}), which could happen during production. Using the introduced notation, it holds

$$NOT = OT - FL_{SP} \tag{11}$$

By making explicit the relation with the losses, Eq. (11) can be also written as

$$NOT = OT - (BL_{IMS} + BL_{RS}) \tag{12}$$

The NOT can also be calculated as the sum of the ECT for all the N_A products, including compliant and non-compliant ones:

$$NOT = N_A \cdot ECT \tag{13}$$

As done for OT and NOT, the VOT can also be expressed as a function of the losses:

$$VOT = NOT - (BL_{PD} + BL_{RY}) \tag{14}$$

The Availability (A) can now be defined as follows:

$$A = \frac{OT}{PPT} = \frac{PPT - FL_{DW}}{PPT} = 1 - \frac{FL_{DW}}{PPT} = 1 - \frac{BL_{EFB} + BL_{S\&A}}{PPT} \tag{15}$$

In the same way, we can express the value of the Performance (P):

$$P = \frac{NOT}{OT} = \frac{OT - FL_{SP}}{OT} = 1 - \frac{FL_{SP}}{OT} = 1 - \frac{BL_{IMS} + BL_{RS}}{OT} \tag{16}$$

The Quality (Q) describes the percentage of compliant production time. It can thus be calculated as follows:

$$Q = \frac{VOT}{NOT} = \frac{NOT - FL_{DF}}{NOT} = 1 - \frac{FL_{DF}}{NOT} \tag{17}$$

Figure 1 summarizes the relationship between all the parameters and the losses introduced so far. Substituting the equations defining A (Eq. (15)), P (Eq. (16)) and Q (Eq. (17)) in Eq. (1), the formulation of the OEE expressed by Eq. (2) is obtained:

$$OEE = A \cdot P \cdot Q = \frac{\cancel{OT}}{PPT} \cdot \frac{\cancel{NOT}}{\cancel{OT}} \cdot \frac{VOT}{\cancel{NOT}} = \frac{VOT}{PPT} \tag{18}$$

V. A FRAMEWORK FOR A SERVICE COMPANY

This section describes how the OEE framework can be adapted to be applied to a *service company*. We distinguish a service company from an industry by the fact that the former generates profits by providing services to its customers, while the latter focuses on manufacturing products. The general characteristics of the service company are:

- Services are provided by Specialized Operators (SOs) through the execution of *activity*.
- Activities are performed at the customer's site.
- The SO is required to personally move to the customer's site, i.e., a travel is required before performing the Activity.
- One single SO carries out multiple Activities at different customer sites during the working day.
- Activities could be of different types.

A. THE WORKING DAY

The *working day* is defined as the total time, during one day, in which the SO is contractually bound to the company. The working day includes the TT (Definition 1) and other possible periods, such as the lunch break. Figure 2 reports the parts of the working day described in this section.

During the working day, we distinguish between the TT and the PPT (Definition 4). The PPT is the total potential time that is available to carry out the activities, which is obtained by removing the Planned Maintenance Time (PMT) from the TT. The PMT is composed of all the Planned Maintenance Stops (PMSs). In turn, PMSs are defined as follows:

Definition 9: A Planned Maintenance Stop (PMS) is defined as any necessary pause for the SO during which no added-value work is performed.

Depending on the motivation of the pause, PMSs can be either included or not included in the TT. The distinction is based on the fact that the time associated with an included PMS is paid by the company to the SO, while a not-included PMS is not paid, although it is part of the working day. Examples of included PMSs are courses, meetings and work permits, while not-included PMSs are lunch breaks.

Formally, we denote with **PMS** the set of PMSs, both included and not included:

$$\mathbf{PMS} = \{PMS_i : i \in [1, N_{PMS}]\} \tag{19}$$

where N_{PMS} is the number of PMSs in the working day. Each element PMS_i corresponds to the duration of the i-th PMS tracked during the working day.

We also define PMT as the sum of all the PMSs:

$$PMT = \sum_{i=1}^{N_{PMS}} InTT_i \cdot PMS_i \tag{20}$$

where

$$InTT_i = \begin{cases} 1, & \text{if } PMS_i \text{ is included in the } TT \\ 0, & \text{if } PMS_i \text{ is not included in the } TT \end{cases} \tag{21}$$

Therefore, PMT is composed of the PMSs that are included in the TT.

According to the approach proposed by Invancic in [23], the PPT is obtained by excluding the contribution of the PMT from the TT:

$$PPT = TT - PMT \tag{22}$$

Finally, we introduce the following concept:

Definition 10: The Observed Planned Productive Time ($OPPT$) is the total observed (measured) duration of all the operations planned in the PPT.

The relationship between PPT and $OPPT$ is that the former represents the expected duration of the operations performed by the SO, while the latter is the measure of the actual duration for such operations.

B. TASKS AND ACTIVITIES

During a working day, the $OPPT$ is divided into a sequence of *tasks*. We denote with τ_i the i-th task. Each task is composed of a travel and the actual operation that must be carried out during the task itself. We consider 3 types of operations: *activities*, *service activities* and PMSs. The latter is defined in Definition 9, while the former are defined as follows:

Definition 11: Activities are operations that are related to the service provided by the company to its customers.

Only a compliant completed activity is paid for by the customer; therefore, only compliant activities are recognized as value-added time.

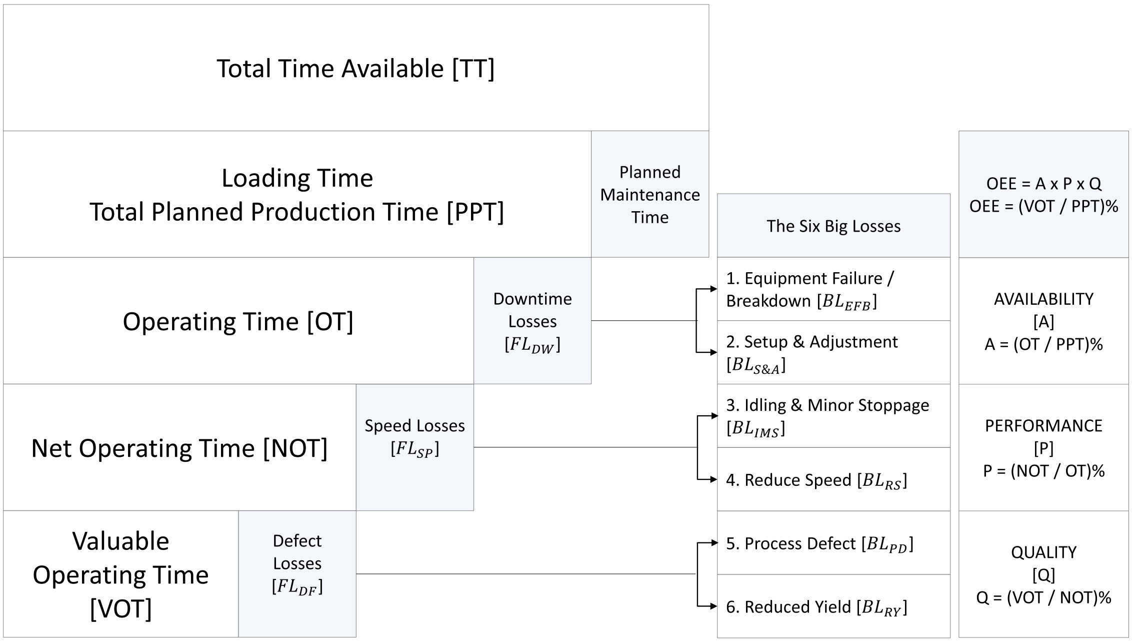


FIGURE 1. **Relationship between all the parameters in the *OEE* definition. This representation is an adaption of a figure proposed in [5] using the notation adopted in this work.**

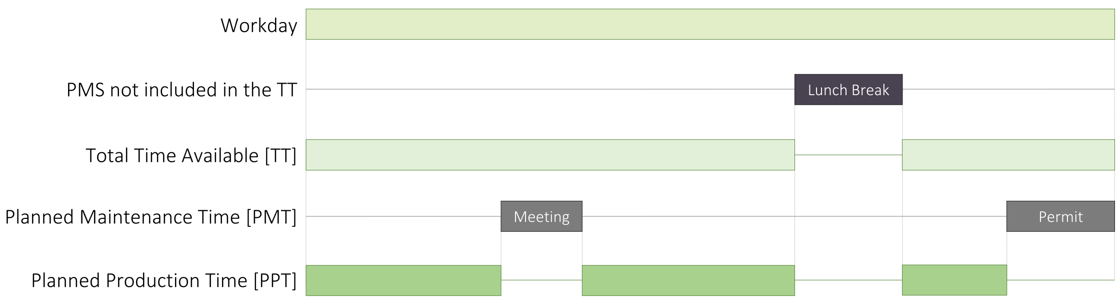


FIGURE 2. **Partitioning of a working day with an example of expected timings for the various sections of the day.**

Definition 12: Service activity are operations that are required to support the work of the *SO*, but they do not generate added value for the company.

Service activity can be either *scheduled* or *unscheduled*. In both cases, a service activity reduces the available time to perform value-added operations.

The type of activities depends on the core business of the considered company. For example, the activities for a telecommunication company can include maintenance interventions on telecommunication lines, while examples of service activities include refuelling of vehicles, picking in the warehouse, etc.

During a working day, there is a total of N tasks composed of N_A activities, N_{SA} service activities and N_{PMS} PMSs. The set $\mathcal{T}$ of tasks performed during a working day can be defined as follows:

$$\mathcal{T} = \{\tau_i : i \in [1, N]\} \tag{23}$$

where $N = N_A + N_{SA} + N_{PMS}$.

To identify the various types of tasks, we use the following notation:

$$\tau_i^A = (Type_i, ECT_i, OCT_i, ETT_i, OTT_i, \mathrm{C}_i, \mathrm{K}_i, \mathrm{S}_i) \tag{24}$$

$$\tau_i^{SA} = (Type_i, ECT_i, OCT_i, ETT_i, OTT_i) \tag{25}$$

$$\tau_i^{PMS} = (Type_i, ECT_i, OCT_i, ETT_i, OTT_i, InTT_i) \tag{26}$$

where

- τ_i^A, τ_i^{SA} and τ_i^{PMS} represent activities, service activities, PMSs.
- $Type_i$ is the type of operation associated with the task;
- ECT_i is the Expected Cycle Time (ECT), the expected (planned) time to complete the task;
- OCT_i is the Observed Cycle Time (OCT), the actual (measured) time required to complete the task;
- ETT_i is the Expected Travel Time (ETT), the expected (planned) duration of the travel;
- OTT_i is the Observed Travel Time (OTT), the actual (measured) duration of the travel;
- C_i is the compliance status of a closed activity (Boolean value);

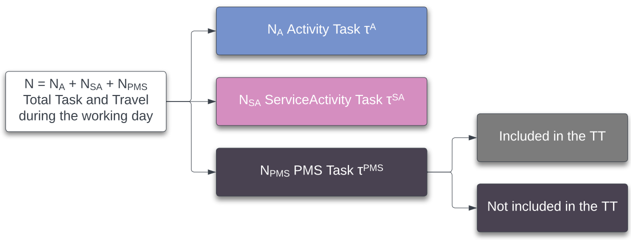


FIGURE 3. The 3 types of tasks considered in the proposed framework.

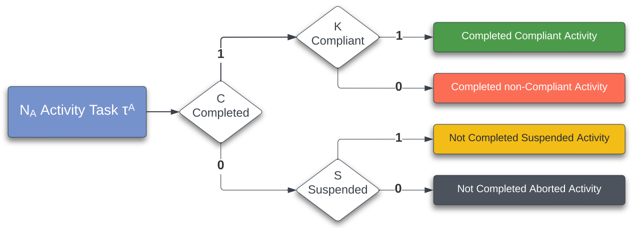


FIGURE 4. The types of activities considered in the framework with their relationships.

- K_i is the completion status of the activity (Boolean value).
- S_i captures the type of problem that occurred to an uncompleted activity; its value is 1 if the activity is suspended, or 0 if it is aborted.
- $InTT_i$ is a *PMS* that is included or not in the *TT*.

Figure 3 summarizes the considered types of tasks and their relationships, while Figure 4 shows the different options for activities. It is worth recalling that, an activity that is non-compliant or uncompleted, will the reworked later by the same or a different *SO*. This becomes a new task, which is accounted for as a new activity.

Interestingly, in the notation adopted for τ_i^A, τ_i^{SA} and τ_i^{PMS}, some parameters are common to the three types of tasks, while other parameters are specific to one type.

The operation carried out during task τ_i, independently from the type of task, is tracked by logging the two following quantities:

- OPE_i^S (*Operational Event - Start*), when the *SO* arrives at the site where the operation is associated with task τ_i must be performed, before starting the work;
- OPE_i^E (*Operational Event - End*) when the *SO* finishes the operation, before leaving the site.

For each *SO* and for each of his working day, a temporally ordered sequence of pairs of events associated with the performed tasks is generated. For each i-th pair of events, the following relationship holds:

$$OPE_i^S < OPE_i^E$$

Therefore, as shown in Figure 5, the τ_i task is performed between OPE_{i-1}^E and OPE_i^E. Formally, the following relationship holds between the start and finishing times of a task τ_i and times tracked for the operation and the travel:

$$OTT_i + OCT_i = OPE_i^E - OPE_{i-1}^E \tag{27}$$

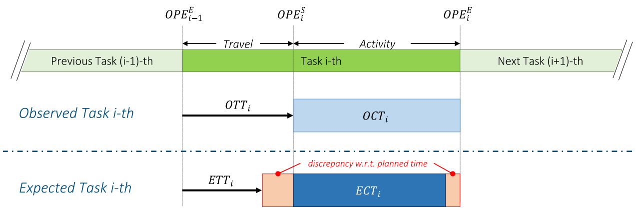


FIGURE 5. The *i*-th task between the preceding and the next one, and the two entities composing it: the travel and the activity.

The start event of the τ_i task (OPE_i^S) divides the period of τ_i into two parts: the first part corresponds to the Observed Travel Time (*OTT*), while the second is the Observed Cycle Time (*OCT*).

Figure 5 shows the i-th task between the previous $(i-1)$-th and the next $(i+1)$-th ones, and the two entities composing it, i.e., the travel and the operation.

The remainder of this section provides formal definitions and details regarding the parameters that are used to define a task.

1) TYPE OF OPERATION AND EXPECTED CYCLE TIME (ECT)

Each task has an associated *Type*. We define with L the number of different types of operations that can be performed by an *SO*. The term ECT_j represents the expected amount of time required to execute the j-th type of operation. We define **ECT** as the set of all the ECT_j:

$$\mathbf{ECT} = \{ECT_j : j = 1 \dots L\} \tag{28}$$

The expected duration of the operation carried out during task τ_i is $ECT_i \in \mathbf{ECT}$.

2) OBSERVED CYCLE TIME (OCT)

The actual (measured) duration of the operation carried out during task τ_i is defined as OCT_i. OCT_i is the difference between the timestamps of the two events associated to the task:

$$OCT_i = OPE_i^E - OPE_i^S \tag{29}$$

OCT is defined as the set of OCT_i, for every τ_i:

$$\mathbf{OCT} = \{OCT_i : i \in [1, N]\} \tag{30}$$

Each element of **OCT** is the actual time taken to perform the corresponding operation.

3) EXPECTED TRAVEL TIME (ETT)

We define with ETT_i the expected time required to reach the site to perform the i-th operation, moving from the previous location. **ETT** is defined as the set of ETT_i for all the travels:

$$\mathbf{ETT} = \{ETT_i : i \in [1, N]\} \tag{31}$$

Some processes require an additional travel to occur after the last task. The expected duration of this optional and additional travel is denoted ETT_{N+1}. The travel starts at the end of the N-th operation, which belongs to the last task τ_N, and allows *SO* to return to the final place of the working day. This place can be either a home or office. This last travel may or may not be considered within the *PPT* without impacting the reliability of the assessment. The first travel, associated with task τ_1, can be also either considered or not without impacting the proposed framework. In Figure 6, the two travels are not considered in the *PPT*; this is outlined by their gray color in the image.

4) OBSERVED TRAVEL TIME (OTT)

The actual (measured) duration of the travel of task τ_i is defined as OTT_i. The time interval between OPE_{i-1}^E, i.e., the end of the previous task, and OPE_i^S, i.e., the start of the current operation, corresponds to the required time to reach the location of the i-th operation moving from the location of the $(i-1)$-th task. The calculation is as follows:

$$OTT_i = OPE_i^S - OPE_{i-1}^E \quad (32)$$

OTT is defined as the set of N OTT_i:

$$\mathbf{OTT} = \{OTT_i : i \in [1, N]\} \quad (33)$$

The duration of the optional last travel from the last task to the place where the working day is considered to be concluded, is denoted with OTT_{N+1}.

5) COMPLIANCE

Compliance is a characteristic that is valid only for the N_A tasks τ_i^A associated with activities. Compliant activities are the ones that bring added value to the company, since they are the only ones paid by customers. The compliance of an activity is determined by the customer once the activity is completed, typically on the basis of contractual agreements. Therefore, they are the only activities that are considered in the calculation of the *OEE*. C_i represents the compliance of activity τ_i^A. It is a Boolean variable that is assigned as follows:

$$C_i = \begin{cases} 1, & \text{if the activity of } \tau_i^A \text{ is compliant} \\ 0, & \text{if the activity of } \tau_i^A \text{ is non-compliant} \end{cases} \quad (34)$$

The set of compliance of all the activities **C** is defined as:

$$\mathbf{C} = \{C_i : \forall i \in [1, N_{A_C}], \tau_i^A \in \mathcal{T}\} \quad (35)$$

while the negated values of the **C** attribute as

$$\overline{\mathbf{C}} = \{\overline{C_i} : \forall i \in [1, N_{A_{\overline{C}}}], \overline{C_i} = 1 - C_i\} \quad (36)$$

where the symbols N_{A_C} and $N_{A_{\overline{C}}}$ denote respectively the number of compliant and non-compliant activities. Therefore, the following relationships hold:

$$N_A = N_{A_C} + N_{A_{\overline{C}}}$$

and

$$\mathbf{C} \cup \overline{\mathbf{C}} = \tau^A$$
$$\mathbf{C} \cap \overline{\mathbf{C}} = \varnothing$$

meaning that an activity can be either compliant or non-compliant.

Given the above definitions, it is worth report that various previously defined terms, under specific assumptions, can be rewritten to match their traditional formulation in the scientific literature. This is the case for the following terms.

If all the activities have the same *ECT*, i.e.,

$$\forall ECT_j \in \mathbf{ECT} : ECT_j = ECT$$

the *VOT* can be calculated as follows:

$$VOT = N_{A_C} \cdot ECT \quad (37)$$

As a consequence, by combining Eq. (37) with Eq. (2), the value of *OEE* can be calculated as follows:

$$OEE = N_{A_C} \cdot ECT / PPT$$

Moreover, two factors composing the *OEE*, namely *P* and *Q*, could be expressed as a function of production factors. Using Eq. (13) and Eq. (16), the value of *P* can be formulated as follows:

$$P = \frac{NOT}{OT} = N_A \cdot ECT / OT$$

On the other hand, by combining Eq. (17) with Eq. (13) and Eq. (37), the value of *Q* can be written as

$$Q = \frac{VOT}{NOT} = N_{A_C} / N_A$$

Interestingly, the value of *Q* results independent from *ECT*. However, to calculate the value of *P* and *Q* it is necessary to know also the number of non-compliant activities.

6) COMPLETION OF ACTIVITIES

We define as K_i the Boolean state of the i-th activity τ_i^A that is completed.

We define with **K** the set of the completion statuses of all the activities associated with tasks τ_i^A:

$$\mathbf{K} = \{K_i : \forall i \in [1, N_A], \tau_i^A \in \mathcal{T}\} \quad (38)$$

An activity can be permanently closed (completed) or not completed. Only a completed and closed activity can be assessed for its compliance. On the other hand, if the activity is not completed, it must be reopened later to be concluded.

An uncompleted activity can be annotated by the cause to improve the possibility of analyzing the phenomenon. This aspect is further specified in Section V-B8.

We introduce the negated values of the **Completion** attribute as

$$\overline{\mathbf{K}} = \{\overline{K_i} : \forall i \in [1, N_A], \overline{K_i} = 1 - K_i\} \quad (39)$$

7) RELATIONSHIP BETWEEN COMPLIANCE AND COMPLETION

Regarding the compliance of activities, an activity can be non-compliant for several reasons. An activity is rejected when, after its completion, the work is considered non-compliant. In case of rejection, the activity is thus completed. The rejection takes place after completion of the activity, for

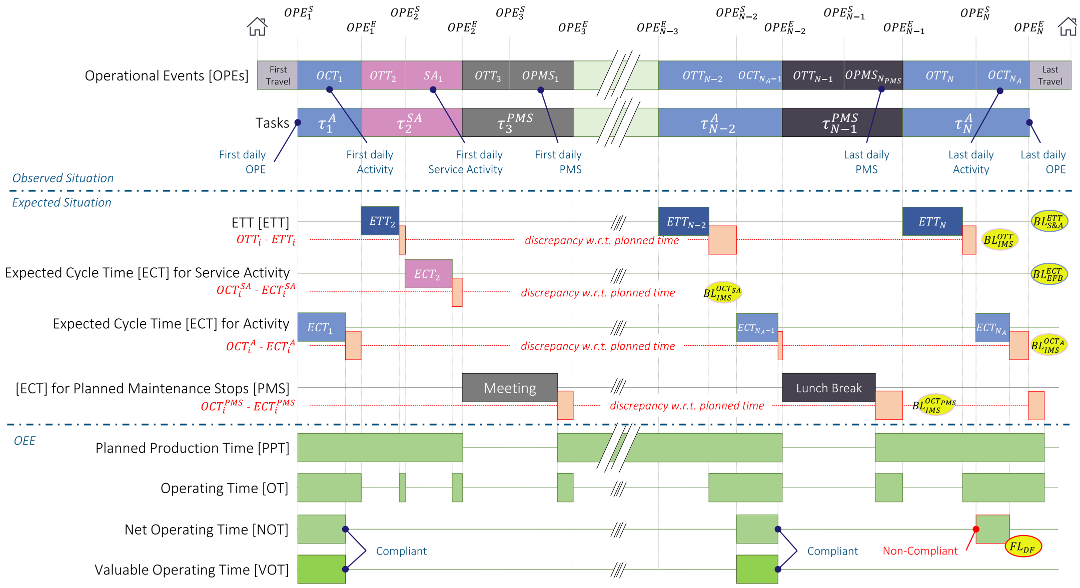


FIGURE 6. Partitioning of a working day with the indication of observed tasks with their observed (measured) timings.

TABLE 1. The possible combinations of the two variables C_i and K_i for activities of tasks τ_i^A. Only 3 of the 4 combinations are possible, as a compliant activity is always completed.

	$K_i = 0$	$K_i = 1$
$C_i = 0$	UnCompleted and Non-Compliant	Completed but Non-Compliant
$C_i = 1$	This case is not possible	Completed and Compliant

example when the quality of the performed work does not comply with contractual terms.

Another case is when an activity can not be completed due to some external problems. An activity is "uncompleted" if it is not possible to complete it and it is necessary to intervene again. Therefore, an uncompleted activity is also non-compliant. In this case, the *SO* may not use all the expected time ECT_i to work the activity of task τ_i^A. Usually, he stops the activity work before its completion.

Table 1 describes the possible combinations of the two variables C_i and K_i for activities of tasks τ_i^A. Only 3 out of the 4 combinations are possible, as a compliant activity is always completed.

8) SUSPENSION AND ABORTION OF ACTIVITIES

An uncompleted activity can be terminated with specific statuses. Alternatively, it can be either *suspended* or *aborted*, according to the following definitions:

- Suspended: An activity is suspended when a temporary problem occurs during the operation. The activity is usually subsequently completed during the same working day.
- Aborted: An activity is aborted when a blocking situation does not allow one to carry on the operation. There is the possibility that the same activity is worked in the following days, once the block is removed. The activity may be assigned to another *SO*.

Suspension and abortion are mutually exclusive conditions for an uncompleted activity.

To capture the state of uncompleted activities, we define as S_i the Boolean state of the *i*-th activity, with the following meaning:

$$S_i = \begin{cases} 1, & \text{if the activity of task } \tau_i^A \text{ is suspended} \\ 0, & \text{if not (the activity of task } \tau_i^A \text{ is aborted)} \end{cases} \quad (40)$$

We define with $\mathbf{S}$ the set of the suspended/aborted states of all the uncompleted activities:

$$\mathbf{S} = \{S_i : \forall i \in [1, N_A], \tau_i^A \in \mathcal{T}\} \quad (41)$$

Being uncompleted, aborted or suspended activities are implicitly non-compliant.

We introduce the negated values of the $\mathbf{S}$ attribute as

$$\overline{\mathbf{S}} = \{\overline{S_i} : \forall i \in [1, N_A], \overline{S_i} = 1 - S_i\} \quad (42)$$

C. REFORMULATION OF RELEVANT TERMS

This section introduces the reformulation of all the relevant that have been presented so far, in view of the fact that different types of activities can be provided by the service company.

1) VALUABLE OPERATING TIME (VOT)

The *VOT*, as defined in Definition 3, is the sum of the *ECT*s of compliant activities only. Formally, it can be calculated as:

$$VOT = \sum_{i=1}^{N_A} C_i \cdot ECT_i \quad \forall \tau_i^A \in \mathcal{T} \quad (43)$$

2) OEE – SIMPLE EQUATION

The complete formulation of the OEE considers that, during a time interval equal to the PPT, the SO can work on a sequence of N_A activities.

We can thus combine Eq. (1) and Eq. (43) to obtain the following formulation of the OEE:

$$OEE = \frac{\sum_{i=1}^{N_A} C_i \cdot ECT_i}{PPT} \quad \forall \tau_i^A \in \mathcal{T} \tag{44}$$

3) NET OPERATING TIME (NOT)

The NOT is the sum of the ECTs of all N_A activities, both compliant and non-compliant:

$$NOT = \sum_{i=1}^{N_A} ECT_i \tag{45}$$

4) P AND Q

Using Eq. (13) and Eq. (15), Eq. (16) that define P can be written as

$$P = \frac{NOT}{OT} = \frac{\sum_{i=1}^{N_A} ECT_i}{OT} = \frac{\sum_{i=1}^{N_A} ECT_i}{PPT - FL_{DW}} \tag{46}$$

Similarly, by combining Eq. (43) and Eq. (45), Q can be written as

$$Q = \frac{VOT}{NOT} = \frac{\sum_{i=1}^{N_A} C_i \cdot ECT_i}{NOT} = 1 - \frac{\sum_{i=1}^{N_A} \overline{C_i} \cdot ECT_i}{\sum_{i=1}^{N_A} ECT_i} \tag{47}$$

D. REPRESENTATION OF PARAMETERS

This section introduces two *views*, namely *PPT View* and *OEE View*, under which the results of the analysis will be represented.

Table 2 shows the 6 losses and the three OEE parameters, OT, NOT and VOT, grouped by the three factors, A, P and Q. Each factor in the first column of the table is associated with the value that corresponds to the sum of the three parameters reported in the second column. The equations that relate the various parameters are reported in the third column.

Each of the parameters in the second column can be normalized in two different ways, leading to the aforementioned views:

- The PPT View is obtained by normalizing with respect to the PPT (column 4 in Table 2).
- The OEE View is obtained by normalizing with respect to the relative sum of the parameters (column 5), i.e., PPT, OT, and NOT, respectively for the parameters of A, P and Q. In this way, the 6 losses normalized according to the OEE framework and the three factors A, P and Q are obtained. It is worth remembering that the sum of the parameters in the OEE View are always equal to 100%.

It is interesting to note how the two views are identical for the parameters related to A, since the normalization parameter of the OEE View is equal to PPT (Eq. (15)). In PPT View, the normalization transforms the NOT parameter into the following

$$NOT\% = NOT/PPT \tag{48}$$

while in the OEE View it becomes the P factor (Eq. (16)).

Regarding the VOT, the normalization in the OEE View transforms the parameter into the Q factor while, in the PPT View, the value of VOT normalized with respect to the PPT corresponds to OEE by definition (Eq. (2)). Consequently, the OEE View is made by 10 parameters, i.e., the 9 parameters reported in column 5, plus the OEE, while the PPT View is made by 9 parameters, reported in column 4, since the last one is the OEE itself.

The numerical example reported in Table 2 shows a comparison of the parameters under the two different views. The value of the 6 losses is set to 10 time units for simplicity, and $PPT = 100$ time units. In the PPT View the losses are always equal to 10%, while in the OEE View the value of the parameters related to P and Q depends on $OT = 80$ and $NOT = 60$ time units.

The same information is represented graphically in Figure 7, which clearly shows the contribution of the losses with respect to PPT for the PPT View and with respect to PPT, OT and NOT, respectively for the parameters of A, P and Q. From left to right, the graph shows how the impact of the losses subtract time from the PPT to obtain the VOT, i.e., the time in which there is the generation of added-value for the company. In each reduction step associated with the losses in the same family, in the PPT View the reductions are always evaluated w.r.t. to PPT, while in the OEE View they are calculated w.r.t. to the impact of the losses of the families in the previous steps.

E. THE TRACKING PROCEDURE

The application of the OEE requires the tracking of each individual OPEs during the working day. The tracking is done by logging the start and the end of the operations carried out in every task, according to the following definition:

Definition 13: The Operational Interval (OPI) is the time interval in which the SO performs an activity, service activity or PMS.

In this sense, OPI_i can be seen as part of the working day that is associated to start (OPE_i^S) and end (OPE_i^E) times.

This section describes the procedure for tracking the working day of the Specialized Operator (SO). The following information are required:

- The SO identifier.
- The OPE_i^S and OPE_i^E associated to the start and the end of the operation.
- Type of operation during the OPI, which can be an activity, service activity, or PMS.
- Optionally, the geographic coordinates of the Operational Interval.

The start of a new operation involves the simultaneous termination of the previous travel in the same task. In this way, the current operation of the SO is known at any moment, with no untracked downtime gaps.

TABLE 2. Theoretical and numerical example to compare the PPT and OEE views.

Index	Parameters	Sum parameter	PPT View Parameter/PPT	OEE View	Example: Time units ($PPT = 100$)	Example: PPT View	Example: OEE View
	BL_{EFB}		BL_{EFB}/PPT	BL_{EFB}/PPT	10	10%	10%
A	$BL_{S\&A}$	PPT (Eq. (10))	$BL_{S\&A}/PPT$	$BL_{S\&A}/PPT$	10	10%	10%
	OT		$OT/PPT = A$	$OT/PPT = A$	80	80%	80%
	BL_{IMS}		BL_{IMS}/PPT	BL_{IMS}/OT	10	10%	12.5%
P	BL_{RS}	OT (Eq. (12))	BL_{RS}/PPT	BL_{RS}/OT	10	10%	12.5%
	NOT		$NOT/PPT = NOT\%$	$NOT/OT = P$	60	60%	75%
	BL_{PD}		BL_{PD}/PPT	BL_{PD}/NOT	10	10%	16.7%
Q	BL_{RY}	NOT (Eq. (14))	BL_{RY}/PPT	BL_{RY}/NOT	10	10%	16.7%
	VOT		$VOT/PPT = OEE$	$VOT/NOT = Q$	40	40%	66.6%

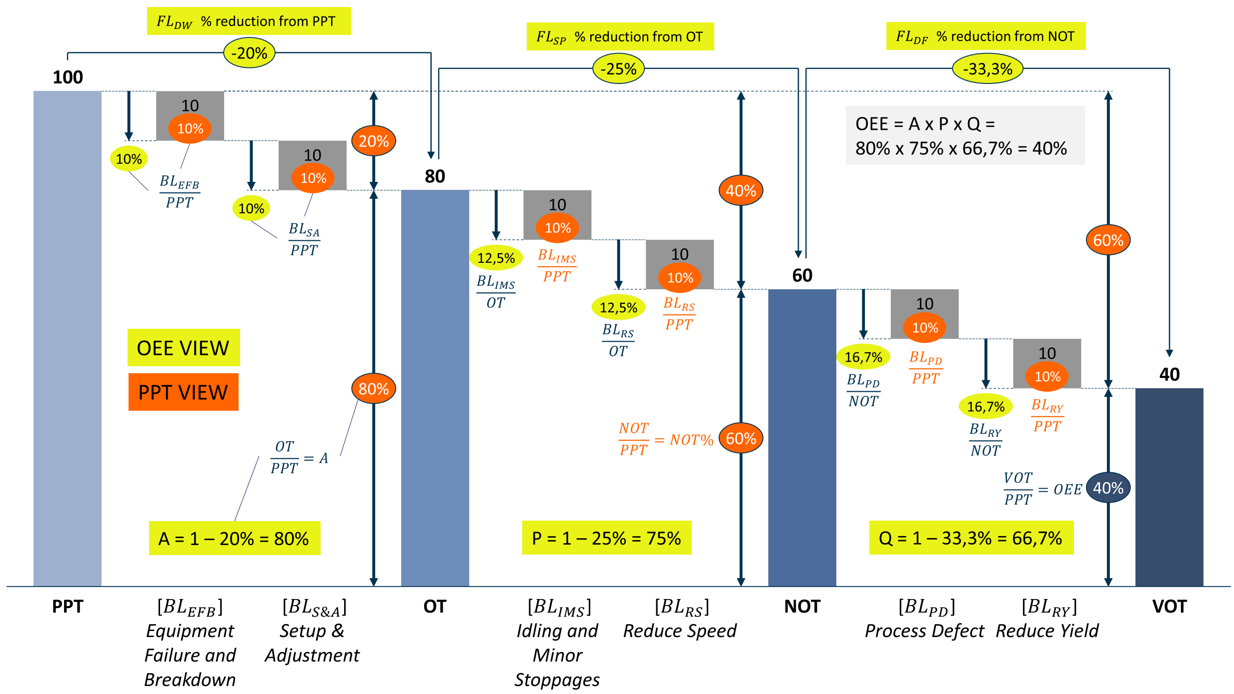


FIGURE 7. Comparison between OEE View and PPT view. The 6 losses have same value equal to 10 time units; *PPT* is equal to 100 time units.

This arrangement does not clearly apply to the very first event of the working day. The first event of the working day is tracked by the start of the first task.

Figure 8 describes the operational process proposed in this work, and the relationships among the different types of operations. In particular, the workflow captures the fact that a travel is always required for moving from one operation to the next one. The pair formed by a travel and an operation composes the task.

The elements that appear in Figure 8 are:

- The activity Operational Interval type is labelled with a "green V"; it is the only Operational Interval type that can generate added value (if the activity is considered compliant).
- The two Operational Interval types, service activity and travel, are tagged with a "red X"; this indicates that they do not generate added value; in other terms, they are losses by definition. Therefore, the travel Operational Interval type is also a service activity. However, it is considered separately due to its great relevance in the definition of the Task.
- Finally, the Planned Maintenance Stop (PMS) Operational Interval type is tagged with a "gray box". A Planned Maintenance Stop (PMS) must be tracked to determine the PPT net time, but it is excluded from the OEE framework.

In terms of relationships among the various types of Operational Intervals, each working day can start and end with any Operational Interval type. An Operational Interval can be followed by any other type of Operational Interval. OPEs are thus associated with the transitions in Figure 8.

F. EXAMPLE OF RELATIONSHIP AMONG RELEVANT FACTORS

This section presents a numerical example showing how the meaning of NOT changes depending on whether it is related to PPT or OT.

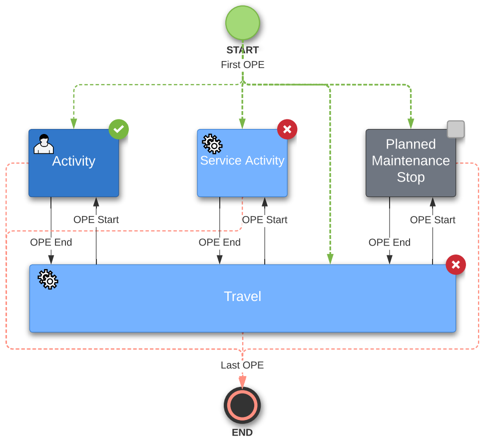


FIGURE 8. **The operational process involving the 3 different types of operations used to represent the *SO* working day. The transition from one operation to another always requires a travel. The green icon identifies an operation that could generate added value, while the red icon is associated with operations that are always losses. The gray icon is associated with the *PMS*, which is not included in the *PPT*.**

The same values of NOT and VOT assume different meanings if compared with different values of OT and NOT, respectively. The ratio between NOT and the available time OT is equal to P (Eq. (16)), while the ratio between VOT and the available time NOT is equal to Q (Eq. (17)). Therefore, P and Q could be different even for the same value of NOT and VOT, since their values also depend on OT and NOT, respectively.

To better understand the relationships among the above quantities, we provide the examples defined by the quantities in Table 3. We consider 8 working days having a value of PPT equal to 8 hours each, and a value of VOT equal to 2 hours. Therefore, the OEE is equal to 25% for every working day. In the calculations, the term $NOT\%$ is defined as in Eq. (48).

For the first 4 working days, the value of NOT is equal to 5 hours; therefore, the value of $NOT\%$ is equal to 63% in every case. However, the value of P must take into account the 5 hours of NOT with respect to the available time, i.e., the OT. The value of P is not simply equal to $NOT\%$; the NOT must be contextualized with respect to OT. Therefore, for the first 4 working days, the values of P are different, although NOT values are the same.

The 8 working days have a value of VOT equal to 2 hours. For the first 4 working days, Q is equal to 40% due to the fact that the values of NOT are the same. However, in the latter 4 working days the value of NOT is different. The OEE, which corresponds to the ratio between VOT and PPT, does not change. On the other hand, Q does change: it grows as the NOT time decreases, as there is less time for non-compliant activities.

VI. LOSSES IN A SERVICE COMPANY

Among the main objectives of this work, there is the assessment of the production efficiency of the SOs. These objectives are mainly addressed by question **Q3**, but also by question **Q1**. Moreover, question **Q2** is also relevant, referring to the assessment of the performance related to the territory. According to such objectives, losses are divided between those attributable to the company and those to the SOs.

The losses that are due to the company depend on all those actions required for preparing the SO for production. By definition, these are the 6 losses that reduce the PPT of the SO, since they reduce the Availability. Table 4 shows the list of losses that are considered in our model. The first 2 losses are caused by the company and impact the Availability. The other 4 losses are attributable to the SO and impact Performance and Quality.

Only compliant activities are considered value-added. Any additional operation performed by the SO during his working day, i.e., service activities or travels, are considered losses by definition. PMSs are also losses, but are not considered in the calculation of the OEE since they are excluded from the PPT by definition.

This section discusses the losses affecting the processes of a service company in relation to the losses modeled in the OEE framework.

A. EQUIPMENT FAILURE AND BREAKDOWN BL_{EFB}

The BL_{EFB} is part of the Down Time Family Losses (FL_{DW}), which is the first of the 3 large families of losses **FL** introduced in Section IV. This loss has a direct impact in reducing Availability. This type of loss includes all the problems and breakdowns of the SO's equipment that do not allow him to adequately carry out his work. This type of loss is not attributable to the SO. All the interruptions must be tracked as service activities, since they contribute to the calculation of BL_{EFB}.

Formally speaking, the loss - denoted as $BL_{EFB}^{ECT_{SA}}$ - can be calculated as follows:

$$BL_{EFB}^{ECT_{SA}} = \sum_{i=1}^{N_{SA}} ECT_i \quad \forall \tau_i^{SA} \in \mathcal{T} \tag{49}$$

It is worth noting that the N_{PMS} ECTs associated to PMSs are not considered in this equation, since PMSs are excluded from the PPT by definition.

One type of loss belonging to this class is related to the refueling of the service vehicle, which is the sum of all refueling service activities during the PPT. Problems or breakdowns that may affect the service vehicle are also part of this type of loss.

Similar problems may be related to defects in the technical equipment provided to the SO, which is necessary for performing the activities. This loss is equal to the sum of all durations of Stock Replenishment service activities during the PPT.

B. SET-UPS AND ADJUSTMENTS $BL_{S\&A}$

The $BL_{S\&A}$ is also part of the Down Time Family Losses (FL_{DW}), which is the first of the 3 large families of losses **FL** introduced in Section IV. Similarly to BL_{EFB}, this loss has a direct impact on reducing Availability. This type of

TABLE 3. 8 sample days to show the values of *P* and *Q*, and the relationships with the values of *OT*, *NOT*, *VOT*.

working day	PPT	OT	NOT	$NOT\%$	P	VOT	Q	OEE
1	8	8	5	5/8=63%	5/8=63%	2	2/5=40%	2/8=25%
2	8	7	5	5/8=63%	5/7=71%	2	2/5=40%	2/8=25%
3	8	6	5	5/8=63%	5/6=83%	2	2/5=40%	2/8=25%
4	8	5	5	5/8=63%	5/5=100%	2	2/5=40%	2/8=25%
5	8	8	7	7/8=88%	7/8=88%	2	2/7=29%	2/8=25%
6	8	7	6	6/8=75%	6/7=86%	2	2/6=33%	2/8=25%
7	8	6	5	5/8=63%	5/6=83%	2	2/5=40%	2/8=25%
8	8	5	4	4/8=50%	4/5=80%	2	2/4=50%	2/8=25%

TABLE 4. The six losses are associated with the family, the impacted parameter and the cause (Company or *SO*).

N.	Loss All Big Losses (**BL**)	Family All Family Losses (**FL**)	Refer to	Attributable to
1	BL_{EFB}	DownTime FL_{DW}	A	Company
2	$BL_{S\&A}$	DownTime FL_{DW}	A	Company
3	BL_{IMS}	Speed FL_{SP}	P	SO
4	BL_{RS}	Speed FL_{SP}	P	SO
5	BL_{PD}	Defect FL_{DF}	Q	SO
6	BL_{RY}	Defect FL_{DF}	Q	SO

loss includes all the necessary operations to enable the SO to perform the assigned activities. Although the work associated with these operations is not a "problem" in the strict sense, it corresponds to necessary service activities scheduled by the company. The corresponding losses are thus attributable to the company.

Within this type of loss, the travel required by the SO to perform a new activity, can be considered a "Set-ups and Adjustments" operation. To draw the comparison with the manufacturing domain, this type of loss occurs when a production unit changes the type of good to produce.

In a working day, there are $N_A + N_{SA}$ travels, one for each performed task of activity (τ_i^A) and service activity (τ_i^{SA}) types. The $BL_{S\&A}^{ETT}$ is defined as the sum of the ETTs for all the travels.

Formally, the loss can be calculated as follows:

$$BL_{S\&A}^{ETT} = \sum_{i=1}^{N_A+N_{SA}} ETT_i \quad \forall \tau_i^A, \tau_i^{SA} \in \mathcal{T} \tag{50}$$

It is worth noting that the N_{PMS} travels associated to PMSs are not considered in Eq. (50) since PMSs are excluded from the PPT by definition.

C. IDLING AND MINOR STOPPAGES BL_{IMS}

The BL_{IMS} is part of the Speed Family Losses (FL_{SP}). They consist in all the short stops that are hard to track accurately. They also account for the lost time that is not tracked in all the other aspects of the model. In other words, they include all the losses that can not be recorded precisely. This loss reduces the PPT, and it is thus attributable to the SO.

Formally, the BL_{IMS} can be calculated as a difference between the PPT, the VOT and all the other sources of losses:

$$BL_{IMS} = PPT - VOT - BL_{EFB} - BL_{S\&A} - BL_{RS} - BL_{PD} - BL_{RY} \tag{51}$$

The equation derives from the relationship in Eq. (6).

The better the loss tracking, the less untracked time falls into the BL_{IMS}. As a straightforward consequence, improvements in the tracking of hidden losses enable a better analysis of overall losses.

1) OBSERVED LOSSES FOR service activities, PMSs, AND TRAVELS

The extra time used by SO for service activities, PMSs, and travels, w.r.t. the estimated time, is a loss attributable to the SO. It is the difference between the observed and the expected durations of the corresponding operations. This extra time can also be negative, if SO takes less time than expected. When the extra time is negative, the related loss is mitigated.

The losses corresponding to the 3 types of operations are denoted as $BL_{IMS}^{OCT_{SA}}$, $BL_{IMS}^{OCT_{PMS}}$ and BL_{IMS}^{OTT}, respectively for the service activities, PMSs and travels.

The 3 losses can be calculated as follows:

$$BL_{IMS}^{OCT_{SA}} = \sum_{i=1}^{N_{SA}} OCT_i - ECT_i \quad \forall \tau_i^{SA} \in \mathcal{T} \tag{52}$$

$$BL_{IMS}^{OCT_{PMS}} = \sum_{i=1}^{N_{PMS}} OCT_i - ECT_i \quad \forall \tau_i^{PMS} \in \mathcal{T} \tag{53}$$

$$BL_{IMS}^{OTT} = \sum_{i=1}^{N} OTT_i - ETT_i \tag{54}$$

D. REDUCED SPEED BL_{RS}

The Reduced Speed (BL_{RS}) losses refer to the extra time taken by the SO to perform the activity. It is part of the Speed Family Losses (FL_{SP}). Their overall effect on the OEE is to reduce Performance. These losses are related to the actual time spent on carrying out the activities. The speed reduction is calculated by comparing the actual time spent versus the expected time to complete the activity. These losses are attributable to the SO.

The following equation allows calculating the total BL_{RS} loss as the sum of the differences between the OCT and ECT of each activity:

$$BL_{RS}^{OCT_A} = \sum_{i=1}^{N_A} OCT_i - ECT_i \quad \forall \tau_i^A \in \mathcal{T} \tag{55}$$

A positive value means that the SO takes longer than expected to perform the activities. Therefore, it is a loss. Otherwise, it corresponds to a gain w.r.t. the expected time.

A deviation from the ECT, both positive and negative, represents a problem that needs to be analyzed since it is a ''defect'' w.r.t. the standard expected behavior.

E. PROCESS DEFECTS BL_{PD}

The Process Defects (BL_{PD}) loss captures the reduction of the Quality due to the completed activities that are non-compliant. It is part of the Defect Family Losses (FL_{DF}).

The following equation defines the term $BL_{PD}^{K\overline{C}}$, which represents the sum of the ECTs for all non-compliant activities ($\overline{C_i} = 1$) that are completed ($K_i = 1$):

$$BL_{PD}^{K\overline{C}} = \sum_{i=1}^{N_A} \overline{C_i} \cdot K_i \cdot ECT_i \quad \forall \tau_i^A \in \mathcal{T} \tag{56}$$

Such non-compliant activities are not paid by the customer.

F. REDUCE YIELD BL_{RY}

The Reduce Yield (BL_{RY}) loss captures the reduction of the Quality due to uncompleted activities for suspension or abortion. It is part of the Defect Family Losses (FL_{DF}).

The following equation defines the term $BL_{RY}^{\overline{K}}$, representing the sum of the ECTs for all the uncompleted activities:

$$BL_{RY}^{\overline{K}} = \sum_{i=1}^{N_A} \overline{K_i} \cdot ECT_i \quad \forall \tau_i^A \in \mathcal{T} \tag{57}$$

Uncompleted activities are also non-compliant.

If the impact of uncompleted activities is significant, it is worth analyzing the composition of $BL_{RY}^{\overline{K}}$ more deeply. Considering Eq. (41), the $BL_{RY}^{\overline{K}}$, as calculated in Eq. (57), can be due to two different causes:

1) $BL_{RY}^{\overline{K}S}$ is defined as the sum of the ECTs for all uncompleted activities that are suspended, i.e., having $S_i = 1$ (see Section V-B8):

$$BL_{RY}^{\overline{K}S} = \sum_{i=1}^{N_A} \overline{K_i} \cdot S_i \cdot ECT_i \quad \forall \tau_i^A \in \mathcal{T} \tag{58}$$

2) $BL_{PD}^{\overline{KS}}$ is defined as the sum of the ECTs for all uncompleted activities that are aborted, i.e., having $\overline{S_i} = 0$ (see again Section V-B8):

$$BL_{RY}^{\overline{KS}} = \sum_{i=1}^{N_A} \overline{K_i} \cdot \overline{S_i} \cdot ECT_i \quad \forall \tau_i^A \in \mathcal{T} \tag{59}$$

The following relationship between losses holds:

$$BL_{RY}^{\overline{K}} = BL_{RY}^{\overline{K}S} + BL_{RY}^{\overline{KS}} \tag{60}$$

Table 5 describes the possible combinations of the 3 variables C (compliance), K (completion) and S (suspension/abortion). Some combinations are not possible. For example, a completed activity can not be suspended or aborted, while an aborted or suspended activity is uncompleted and can not thus be compliant.

G. SUMMARY OF THE LOSSES

A summary of all the losses is reported in Table 6. In the table, every single loss, described in the previous sections, is associated with the family of the loss itself, the corresponding big loss, the impacting factor and the cause of the loss.

H. USING OCT INSTEAD OF ECT FOR MORE ACCURATE CALCULATIONS

This section addresses question **Q5** by describing the use of OCT instead of ECT for more accurate calculations of P and Q.

Uncompleted activities are suspended or postponed due to the lack of the necessary operational conditions. In most cases, this situation is detected almost immediately after the beginning of the activity. This affects the OCT, since an uncompleted activity has an observed duration that can be much shorter than the expected one (ECT). For this reason, if ECT is used for uncompleted activities in the calculation of OT, this determines an overestimation of the Performance. This because an activity would appear to be completed in a very short time, instead it is prematurely terminated since the necessary conditions to carry out the activity are not achieved.

Since the value of VOT, and thus the OEE, only depends from the ECT of completed and compliant activities, the overestimation of P determines an underestimation of Q. Figure 9 provides an example showing the difference in using ECT and OCT in the calculation of P and Q.

The use of OCT instead of ECT for uncompleted activities solves the problem of the overestimation of P and the underestimation of Q. The example reports two cases: the use of the standard OEE, and the use of the OCT in the calculations. The two cases are referred to as *Standard OEE* and *Compensated OEE*, respectively. Standard and Compensated cases use ECT and OCT – respectively – for 2 suspended and 2 aborted activities, to calculate the indicated losses. As can be seen by the reported numbers, there is a difference in both BL_{RS} and BL_{RY} (−8 and +8 time units, respectively). However, due to the formulation of the losses stated in Eq. (6), these differences compensate for each other. In the equation, all but the terms BL_{RS} and BL_{RY} remain unchanged. Therefore, a positive contribution of one loss must correspond to the equivalent negative contribution of the other one. On the other hand, the value of NOT is affected by the change of the BL_{RS} (see Eq. (11)), changing its value from 27 to 19 time units. The NOT appears in the formulation of P and Q,

TABLE 5. The four possible states of an activity, resulting from the combination of the 3 variables C_i, K_i and S_i. Only the possible combinations are shown. The n.a. acronym stands for "not applicable".

Activity status	Completion (C_i)	Compliance (K_i)	Suspended (S_i)
Completed and Compliant	1	1	n.a.
Completed and Non-Compliant	1	0	n.a.
Uncompleted and Suspended	0	0	1
Uncompleted and Aborted	0	0	0

TABLE 6. Summary of all the considered losses, associated with the family, the big loss, the impacting factor and the cause of the loss.

Loss	OEE factor	Cause	Loss Family	Big Loss
$BL_{EFB}^{ECT_{SA}}$	A	Company	FL_{DW}	BL_{EFB}
$BL_{S\&A}^{ETT}$	A	Company	FL_{DW}	$BL_{S\&A}$
BL_{IMS}^{OTT}, $BL_{IMS}^{OCT_{SA}}$, $BL_{IMS}^{OCT_{PMS}}$	P	SO	FL_{SP}	BL_{IMS}
$BL_{RS}^{OCT_A}$	P	SO	FL_{SP}	BL_{RS}
BL_{PD}^{KC}	Q	SO	FL_{DF}	BL_{PD}
$BL_{RY}^{\overline{K}S}$, $BL_{RY}^{\overline{KS}}$	Q	SO	FL_{DF}	BL_{RY}

respectively as the numerator and denominator of Eq. (16) and Eq. (17). This fact leads to different values of P and Q, which are respectively overestimated and underestimated in the Standard w.r.t. Compensated cases.

For the above purpose, Eq. (13) that defines the NOT can be reformulated. The following equation, keeps into account the contribution of completed activities (for which $K_i = 1$) using the ECT, and the contribution of uncompleted activities using OCT ($\overline{K_i} = 1$):

$$NOT = \sum_{i=1}^{N_A} (K_i \cdot ECT_i + \overline{K_i} \cdot OCT_i) \quad \forall \tau_i^A \in \mathcal{T} \tag{61}$$

Moreover, Eq. (55) can be re-formulated as follows, where the term K_i is explicitly taken into account:

$$BL_{RS}^{OCT_A} = \sum_{i=1}^{N_A} K_i(OCT_i - ECT_i) \quad \forall \tau_i^A \in \mathcal{T} \tag{62}$$

In this new formulation of $BL_{RS}^{OCT_A}$ the contribution of uncompleted activities is suppressed since $K_i = 0$.

The same considerations are made for $BL_{RS}^{OCT_A}$ can be applied to $BL_{RY}^{\overline{K}}$. Again, uncompleted activities are suspended or postponed due to a lack of the necessary operating conditions. If ECT is used for uncompleted activities, it determines an overestimation of the P, which is compensated by an increase in $BL_{RY}^{\overline{K}}$ and, therefore, a reduction of the Q.

Similarly to Eq. (62), Eq. (57) that defines $BL_{RY}^{\overline{K}}$ can be re-formulated as follows:

$$BL_{RY}^{\overline{K}} = \sum_{i=1}^{N_A} \overline{K_i} \cdot OCT_i \quad \forall \tau_i^A \in \mathcal{T} \tag{63}$$

Eq. (58), which defines $BL_{RY}^{\overline{K}S}$, can also be reformulated as

$$BL_{RY}^{\overline{K}S} = \sum_{i=1}^{N_A} \overline{K_i} \cdot S_i \cdot OCT_i \quad \forall \tau_i^A \in \mathcal{T} \tag{64}$$

Moreover, the new equation of $BL_{RY}^{\overline{KS}}$, which is a reformulation of Eq. (59), becomes the following:

$$BL_{RY}^{\overline{KS}} = \sum_{i=1}^{N_A} \overline{K_i} \cdot \overline{S_i} \cdot OCT_i \quad \forall \tau_i^A \in \mathcal{T} \tag{65}$$

VII. CASE STUDY

The proposed framework has been applied to a service company whose characteristics are reported and discussed in this section.

The considered company is SIRTI S.p.A. The company was founded in Italy in 1921. It operates in the telecommunications, energy and digital solutions sectors. Its main market area is the telecommunications field. SIRTI is formed by more than 3, 800 employees (year 2021). The considered context of our analysis targets the activities performed by SIRTI's SOs on the Italian telephone Access Network (AN).

The clients of SIRTI are the primary telecommunications companies. Such clients provide a fixed network service to the end user, including Voice, Internet and Voice, and Internet. The services provided by SIRTI to its clients refer to several aspects related to the maintenance of physical communication lines. The telecommunication client companies send a request to SIRTI every time they need an intervention on the field for the maintenance of the AN.

On the territory, the company is organized into *Cost Centers (CCs)*. A CC is bound to a geographical area. Each CC is associated with one or more warehouses and headquarters. There is a total of 18 CCs. The CCs are grouped in 5 territories. Figure 10 shows the map of territories and CCs.

A. DATA SOURCE AND COLLECTION

The SIRTI branch dedicated to the services related to the AN is composed of 1, 200 employees. The data that is used to evaluate the proposed framework tracks the working days of 973 SOs on a period of 1 year in 2019, from January 1st to December 31st. The data collection was done with the informed consent of the employees and comply with the laws on data protection.

The data collected by technicians (SOs) are related to activities with economic value but also with legal responsibility. The operational information used in this thesis and other technical information are not only recorded for internal use at Sirti but it is also sent to customers' information systems. In the event of a legal dispute by customers, these data have legal validity. Both internal and customer audits are periodically carried out on OPEs recordings to verify their quality and correctness.

Every task related to the AN is assigned to the SO by a procedure performed by the company's workforce management information system. This allows for the dynamic planning of tasks based on the SO's availability, skills, and their position. Moreover, it aims at minimizing the travel time on the territory.

Each activity is uniquely identified by a number and it is associated with the end user's telephone line. Different

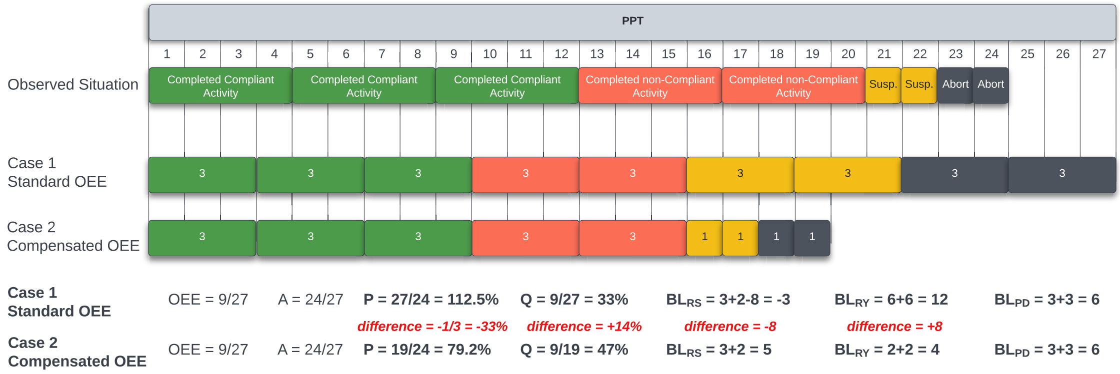


FIGURE 9. Example showing the difference in using *ECT* and *OCT* in the calculation of *P* and *Q*. The use of *OCT* instead of *ECT* for uncompleted activities solves the problem of overestimation of *P* and underestimation of *Q*. Colors are used according to the palette adopted in Figure 4.

activities, with different unique identifiers, are possible for the same telephone line. Two or more activities that start simultaneously can never occur for the same *SO*.

Each *SO* is equipped with a smart device, tablet or smartphone. When on the field, the *SO* uses his smart device to report the start and the end time of each operation, in real-time. This allows the timely detection of the *OPE*s associated with the task assigned and performed by the *SO*.

Considering the observation period of 1 year, during which 952 *SO*s performed their tasks, a total of 66, 562 8-hours working days have been tracked, equivalent to 532, 496 hours. A total of 474, 849 activities have been executed during this period. The *SO* is considered to work at a single *CC* in each specific working day.

Table 7 summarizes the main data.

VIII. ANALYSIS OF THE TERRITORIAL ORGANIZATION OF THE COMPANY

This section presents an analysis of the territorial organization of the company, and their *SO*s. The goal of the analysis is to show the contributions of different territories and *CC*s to the performance of the whole company.

The analysis of the performance of *SO*s is observable by grouping the results according to the *CC*s or to the territory where the *SO*'s work is carried out.

There are no mixed days, where one *SO* works on two different *CC*s. However, a *SO* can work at different *CC* on different working days. It is thus possible to distinguish two classes of working days: "*primary*", if the *SO* works at its own *CC* and "*secondary*" if *SO* works at a different *CC*.

Each individual *SO* executes a specific number of activities during the observed period. This number mainly depends on the number of working days, but does not represent a fundamental information to evaluate the performance of the *SO*s. In fact, the evaluation of the performance is strongly affected by the *ECT* of the activities, and not only on their number.

Each activity is associated with its co-ordinates, latitude and longitude. Using the position of all the activities executed by a *SO*, it is possible to associate a *center of gravity* to

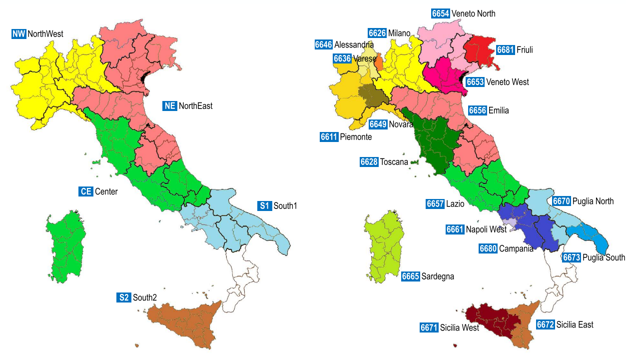


FIGURE 10. The maps of 5 territories (left) and 18 *CC*s (right).

each *SO*. A center of gravity, or *gravity point*, corresponds to the place where the *SO* works more often. For the calculation of the gravity points, only the activities performed by the *SO* in his primary *CC* were considered. This is because the activities executed in secondary *CC*s are considered outliers that would shift the gravity points.

The results related to the center of gravity are reported in two distinct sections: In Section VIII-A, the analysis is done by territory, while in Section VIII-B it is done by *CC*.

For the evaluation of the *OEE* for each *SO*, the *OEE* value is calculated using Eq. (2), considering the working days and activities of the specific *SO*. The number of working days associated with each *SO*, therefore, becomes an interesting parameter to analyze.

Figure 11 shows a scatter plot with the relationship between the value of the *OEE* and the number of working days for each *SO*.

Figure 11a represents the LOESS Curve Fitting (Local Polynomial Regression). This is a method for fitting a smooth curve between two variables, or fitting a smooth surface between an outcome and up to four predictor variables. The curve shows an increase in the value of the *OEE* as the number of working days performed by *SO*s increases. This suggests that greater work continuity and experience are related to higher performance.

TABLE 7. The relevant numbers associated to the source of data and its characteristics.

SOs	8-hour days	Hours	Activities
952	66,562	532,496	474,849

Figure 11b shows the same data in a scatter plot with a 2-dimensional kernel density estimation. Level curves show an agglomeration of SOs around 100 working days and $OEE = 50$.

A. ANALYSIS OF SO BY TERRITORY

The number of SOs and the executed activities, divided by primary and secondary territories, are shown in Figure 8. As can be seen in the *#SO* column, only 16 SOs work in a secondary territory. The number of executed activities in a secondary territory corresponds to 949, which is equal to 0.2% of all activities. It is thus considered as not relevant for the analysis. Therefore, in the calculation of the gravity points, only the activities carried out in the primary CC are considered.

Figure 12 represents the 952 gravity points, one for each SO. The color of the points distinguishes the belonging to one of the 5 territories.

B. ANALYSIS OF SPECIALIZED OPERATORS BY COST CENTER

The number of SOs and executed activities, divided among the CCs, are shown in Figure 9. There are 222 SOs working in a secondary CC. The number of executed activities in a secondary CC is 13, 691; it corresponds to 2.88% of all activities. This percentage is higher w.r.t. the one presented in Section VIII-A for territories. This is motivated by the fact that CCs are smaller than territories, and therefore it is easier for SOs to be loaned between adjacent CCs.

Figure 13 shows the 952 gravity points, one for each SO. The color of points distinguishes the belonging to the different CCs.

It is interesting to note that different SOs typically have non-overlapping gravity points. This is because different SOs are assigned to specific areas within the same CC, to leverage their knowledge and experience about the environment.

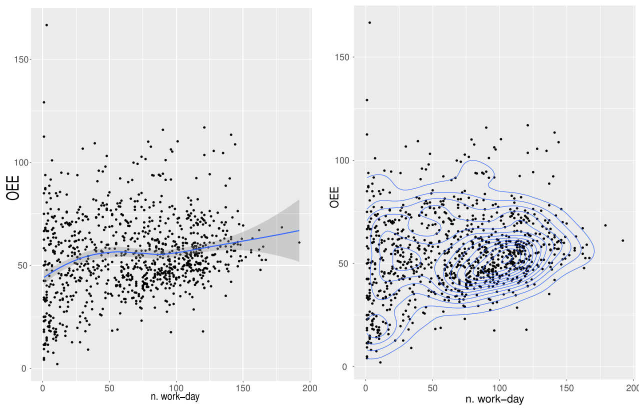
IX. RESULTS

The data gathered for the SIRTI company described in Section VII have been elaborated and are presented under several viewpoints in this section.

The goal of the results is to show how the use of the proposed framework can help in understanding the underlying behavior and performance of the SOs during their work, and to answer the questions posed in this paper. The evaluation is done using all the working days. The obtained results are presented under the two different views introduced in Section V-D:

1) PPT View: As an impact on PPT. Each time interval is expressed as a percentage of the PPT. To obtain the percentage, the time interval itself is divided by the PPT value.
2) OEE View: According to the OEE framework.

The results of each view are presented for the whole workforce and according to the territorial organization of the company, i.e., grouping by territory and by CC.



(a) LOESS Curve Fitting (Local Polynomial Regression). (b) 2D Kernel density estimation.

FIGURE 11. ***OEE* value and number of working days for each *SO*. Each point in the figures represents a single *SO*.**

TABLE 8. The number of *SO*s and executed activities, grouped by territory. The 952 *SO*s and the executed activities are grouped among the 5 territories. The numbers are divided into two categories, primary or secondary, based on the working area of the *SO*s.

TERRITORY	PRIMARY				SECONDARY				Total			
Territory	#SO	%SO	#Act	%Act_row	#SO	%SO	#Act	%Act_row	**#SO**	**%SO**	**#Act**	**%Act_row**
CE	154	16,18%	73346	99,84%	1	6,25%	117	0,16%	**155**	**16,28%**	**73463**	**100,00%**
NE	203	21,32%	109057	99,37%	11	68,75%	689	0,63%	**214**	**22,48%**	**109746**	**100,00%**
NW	183	19,22%	76531	99,87%	5	31,25%	102	0,13%	**185**	**19,43%**	**76633**	**100,00%**
S1	302	31,72%	166615	99,98%	1	6,25%	32	0,02%	**303**	**31,83%**	**166647**	**100,00%**
S2	110	11,55%	48351	99,98%	1	6,25%	9	0,02%	**111**	**11,66%**	**48360**	**100,00%**
Total	**952**	**100,00%**	**473900**	**99,80%**	**16**	**100,00%**	**949**	**0,20%**	**952**	**100,00%**	**474849**	**100,00%**

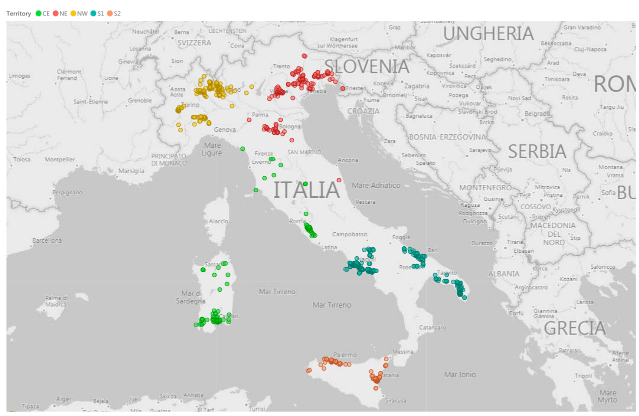


FIGURE 12. The 952 gravity points, one for each *SO*. Different colors are used for each of the 5 territories.

A. RESULTS FOR THE PPT VIEW

This section presents the results for the PPT View. For a better understanding, such results are shown in two equivalent forms: 1) as absolute values of timing duration, and 2) as percentage of PPT.

TABLE 9. The number of *SO*s and executed activities, divided among the *CC*s. The 952 *SO* and the executed activities are divided by the 18 *CC*s. The numbers are divided into two categories, primary or secondary, based on the *CC* where the *SO*s work.

CC	PRIMARY				SECONDARY				Total			
Territory	#SO	%SO	#Act	%Act_row	#SO	%SO	#Act	%Act_row	#SO	%SO	#Act	%Act_row
CE	**154**	**16,18%**	**73346**	**99,84%**	**1**	**0,45%**	**117**	**0,16%**	**155**	**13,20%**	**73463**	**100,00%**
6628	7	0,74%	1217	100,00%					**7**	**0,60%**	**1217**	**100,00%**
6657	66	6,93%	30925	100,00%					**66**	**5,62%**	**30925**	**100,00%**
6665	81	8,51%	41204	99,72%	1	0,45%	117	0,28%	**82**	**6,98%**	**41321**	**100,00%**
NE	**203**	**21,32%**	**107268**	**97,74%**	**62**	**27,93%**	**2478**	**2,26%**	**265**	**22,57%**	**109746**	**100,00%**
6653	52	5,46%	23034	98,95%	4	1,80%	244	1,05%	**56**	**4,77%**	**23278**	**100,00%**
6654	70	7,35%	35169	95,67%	43	19,37%	1590	4,33%	**113**	**9,63%**	**36759**	**100,00%**
6656	44	4,62%	26947	99,99%	1	0,45%	2	0,01%	**45**	**3,83%**	**26949**	**100,00%**
6681	37	3,89%	22118	97,18%	14	6,31%	642	2,82%	**51**	**4,34%**	**22760**	**100,00%**
NW	**183**	**19,22%**	**71951**	**93,89%**	**94**	**42,34%**	**4682**	**6,11%**	**277**	**23,59%**	**76633**	**100,00%**
6611	35	3,68%	12578	99,28%	6	2,70%	91	0,72%	**41**	**3,49%**	**12669**	**100,00%**
6626	53	5,57%	26313	94,80%	17	7,66%	1444	5,20%	**70**	**5,96%**	**27757**	**100,00%**
6636	30	3,15%	13436	91,47%	12	5,41%	1253	8,53%	**42**	**3,58%**	**14689**	**100,00%**
6646	30	3,15%	8592	90,28%	27	12,16%	925	9,72%	**57**	**4,86%**	**9517**	**100,00%**
6649	35	3,68%	11032	91,93%	32	14,41%	969	8,07%	**67**	**5,71%**	**12001**	**100,00%**
S1	**302**	**31,72%**	**160595**	**96,37%**	**53**	**23,87%**	**6052**	**3,63%**	**355**	**30,24%**	**166647**	**100,00%**
6661	107	11,24%	50617	91,63%	31	13,96%	4626	8,37%	**138**	**11,75%**	**55243**	**100,00%**
6670	52	5,46%	33060	100,00%					**52**	**4,43%**	**33060**	**100,00%**
6673	63	6,62%	39360	99,66%	5	2,25%	136	0,34%	**68**	**5,79%**	**39496**	**100,00%**
6680	80	8,40%	37558	96,68%	17	7,66%	1290	3,32%	**97**	**8,26%**	**38848**	**100,00%**
S2	**110**	**11,55%**	**47998**	**99,25%**	**12**	**5,41%**	**362**	**0,75%**	**122**	**10,39%**	**48360**	**100,00%**
6671	50	5,25%	17442	99,60%	2	0,90%	70	0,40%	**52**	**4,43%**	**17512**	**100,00%**
6672	60	6,30%	30556	99,05%	10	4,50%	292	0,95%	**70**	**5,96%**	**30848**	**100,00%**
Total	**952**	**100,00%**	**461158**	**97,12%**	**222**	**100,00%**	**13691**	**2,88%**	**1174**	**100,00%**	**474849**	**100,00%**

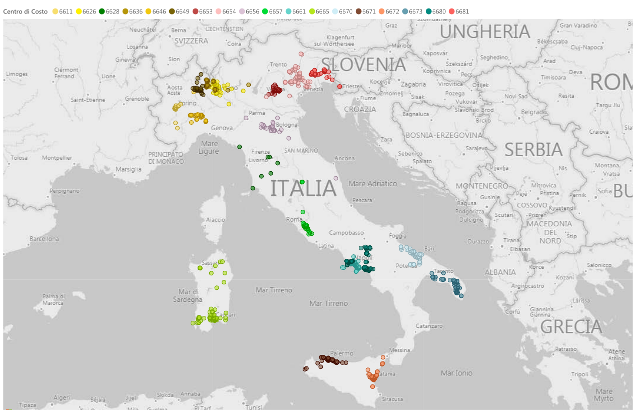


FIGURE 13. The 952 gravity points, one for each *SO*. They are divided between the 18 *CC*.

1) RESULT FOR THE TOTAL WORKFORCE

The bar graph in Figure 14a shows the average value of each loss for the entire workforce. The weights of the working days are all equal, since the *PPT* is the same and equal to 480 minutes. As can be seen in the figure, the Reduced Speed (BL_{RS}) is negative, and thus represents a gain of time, i.e., less time is required to perform the activities. In other words, the sum of all OCTs (the measured time) is less than the sum of all ECTs (the expected time) for the performed activities. Its value increases the total available time during a working day from 480 minutes, which is the value of PPT, to 541.2 minutes. This is because the value of VOT has been increased by the BL_{RS}, which is equal to 61.2 minutes, representing the average difference between OCT and ECT in each working day. The sum of VOT and **BL** corresponds to the PPT, i.e., 480 minutes, as defined in Eq. (6).

The situation of all the Family Losses is the following:

1) FL_{DW}, associated with the Availability, involves a loss of approximately 1 hour and 9 minutes. A total of 50 minutes is the average expected time spent on travels during the working day ($BL_{S\&A}$). The remaining losses, equal to 18 minutes, are due to the time spent for service activities such as supplying at the warehouse or refueling (BL_{EFB}). These losses are associated to the company.
2) FL_{SP}, associated to the Performance, involves a slight gain of 11 minutes.
3) FL_{DF} leads to a loss of 2.5 hours. A portion of these time equal to 1 hour and 20 minutes is due to non-compliant activities ($BL_{PD}^{\overline{KC}}$), while 1 hour and 10 minutes is caused by the uncompleted activities (BL_{RY}), i.e., due to suspensions ($BL_{RY}^{\overline{KS}} = 45.6$ minutes) and abortions ($BL_{RY}^{\overline{KS}} = 24.6$ minutes).

The same results can be observed as a fraction of the PPT. All the reported quantities, i.e., VOT and **BL**, are thus divided by $PPT = 480$ minutes. This result is reported in Figure 14. The bar chart reaches 112.8%. This value is greater than 100% since it is obtained by dividing 541.2 minutes by 480. A percentage equal to 31.3% of the PPT is lost due to Quality problems. Such problems are related to the FL_{DF} family loss, corresponding to activities that are non-compliant, suspended or aborted.

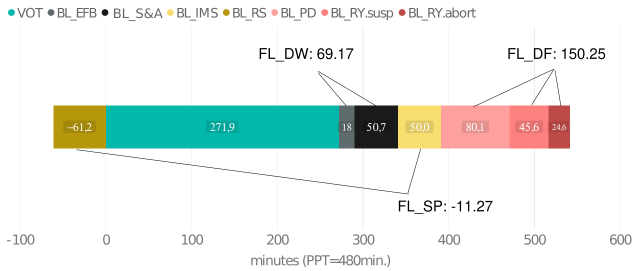
2) RESULTS BY TERRITORY

The same information discussed for the total workforce is presented for the 5 territories.

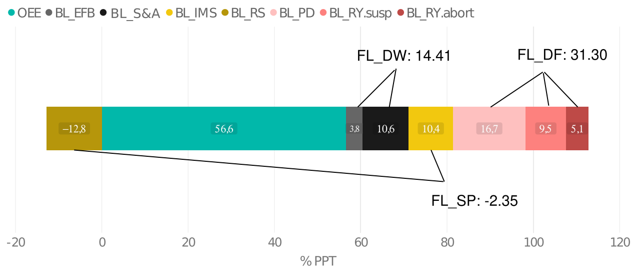
Table 10a reports the results, expressed in minutes, and highlighted with a color scale ranging from dark green to red, representing low to high impact, respectively. Icons with 3 different colors are used, according to the status report code criterion *Red Amber Green (RAG)*. The colors are assigned to the icons by column. For each column, the range between the minimum and maximum values is divided into 3 intervals of same size. The red color (highest interval) indicates when there are more losses, and thus there are *critical* problems, amber (intermediate interval) is used when there are *potential* problems and green (lowest interval) in case of *minor* problems. Different icon shapes are used for the 6 losses and the 3 family losses.

The table shows heterogeneity of the results among the territories. In particular, the following observations can be done:

1) The *NW* territory, which reaches the best result in terms of OEE, has good A, moderate P, but very good Q. In fact, the value of Q is about 7 percentage points above the overall group average. This is mainly due to a low value of BL_{RY}.
2) The second best territory is the *NE*. The territory does not have a good value of A, due to the long travels, but it catches up on P. The value of Q is in the average of the group. However, it suffers from a high number of suspended activities.
3) The *CE* territory is the third in terms of OEE. This has the worst value for A; this is explained by the fact that it is the largest territory, leading to the longest distances



(a) Average absolute value of each loss for the entire group and for all working days, in minutes.



(b) Percentage impact of each loss for the overall group and for all working days with respect to PPT (PPT View).

FIGURE 14. Results for the total workforce in minutes and as percentage of *PPT*. These latter are associated to the PPT view.

to cover. The P of the territory is above the average but it loses in terms of Q, mainly due to the abortions of the activities.

4) The territories of the south, i.e., *S1* and *S2*, do not have a good Availability; the Performance is below the average and the Quality is affected by the high value of BL_{PD}.

The same results can be expressed as a fraction of the PPT, as reported in Table 10b.

3) RESULT BY *CC*

Table 11a shows the results by CC, with the entities measured in minutes. There is heterogeneity among the CCs, also when they belong to the same territory.

The results by CC are related to the results by territory presented in Section IX-A2. In fact, the weighted average of CCs determine the results for the territories. The average is weighted by the number of working days.

On the other hand, within a territory, the behavior of specific CCs can be very different. For example, in the *NW* territory, which is the best performer, there is a remarkable distinction between the OEE value obtained by different CCs.

The same results can be observed as a fraction of the PPT, as shown in Table 11b.

B. RESULTS FOR THE OEE VIEW

This section presents the results under the OEE View.

1) RESULTS FOR THE WHOLE WORKFORCE

The result reported in this section represents the main contribution to the understanding of the performance of the company as a whole, and allows to easily visualize the impact of the various losses.

The presented results refer to the OEE View. The impacts of factors and the **BL** are shown in Figure 15. The percentage impact of each term, with respect to the PPT, is also reported in brackets for comparison with the PPT View.

The graph can be read from left to right. Starting from the value of PPT (480 minutes, corresponding to the 100% of the daily working time), the figure shows the contribution of every single loss that leads obtaining the final value of VOT (271.9 minutes), which is by definition the actual time spent in valuable operations. The value of OEE, calculated with Eq. (2), is equal to $271.9/480 = 56.64\%$.

The contributions of BL_{EFB} and $BL_{S\&A}$, which are the 2 big losses related to A, are -18.5 minutes (-3.85% of PPT) and -50.7 minutes (-10.57% of PPT), respectively. The sum of the 2 big losses, which corresponds to the value of FL_{DW}, is equal to -69.2 minutes (-14.41%). Consequently, the value of OT is 410.8 minutes. The value of A is 85.59%, which is equivalent to the ratio between OT and PPT.

The contributions of BL_{IMS} and BL_{RS}, which are the 2 losses related to P, are -50.0 minutes (-12.16% of OT) and $+61.2$ minutes ($+14.91\%$ of OT), respectively. The sum of the 2 losses, which corresponds to the value of FL_{SP}, is equal to $+2.74\%$ of OT and, consequently, the value of P is equal to 102.74%. The impacts of BL_{IMS} and BL_{RS} on PPT are -10.41% and $+12.76\%$; their sum is $+2.35\%$. As a result, the contribution of FL_{DW} (-14.41%) and FL_{SP} (2.74%) gives a total reduction of PPT equal to -12.06%, since

$$FL_{DW} + FL_{SP} = -14.41\% + 2.74\% = -12.06\%$$

The value of NOT is 422.1 minutes and it is equal to 87.94% of the PPT. The value 87.94% can also be obtained as $100\% - 12.06\%$.

The contribution of BL_{RY} is divided between $BL_{RY}^{\overline{KS}}$ and $BL_{RY}^{\overline{KS}}$. The contributions of BL_{PD}, $BL_{RY}^{\overline{KS}}$ and $BL_{RY}^{\overline{KS}}$ related to Q, are -80.1 minutes (-18.98% of NOT), -45.6 minutes (-10.79% of NOT) and -24.6 minutes (-5.82% of NOT), respectively. The sum of the 3 losses, which correspond to the value of FL_{DF}, is equal to -35.58% of NOT and, consequently, the value of Q is 64.41%. The impacts of these 3 losses on PPT are -16.69%, -9.49% and -5.12%; their sum is -31.30%. As a result, the total reduction of the PPT is due to the contribution of FL_{DW}, FL_{SP} and FL_{DF}, as follows:

$$\begin{aligned} FL_{DW} + FL_{SP} + FL_{DF} &= -14.41\% + 2.74\% - 31.30\% \\ &= -43.36\% \end{aligned}$$

The value of VOT is 271.9 minutes and it is equal to 56.64% of the PPT. The OEE value is equal to 56.64%, and it can also be obtained as $100\% - 43.36\%$.

According to the formulation of the OEE, and using the terms that appear in Figure 15, its value can also be calculated in the following ways:

- as a function of the total loss: $100\% - \mathbf{BL}_*$;

TABLE 10. Results for the total workforce by territories in minutes and as percentage of *PPT*. These latter are associated to the PPT view.

Territory	# w.d.	% w.d.	VOT (min)	BL_EFB	BL_S&A	FL_DW	OT (min)	BL_IMS	BL_RS	FL_SP	NOT (min)	BL_PD	BL_RY_susp	BL_RY_abort	BL_RY	FL_DF
CE	10833	16,28%	276,11	24,28	51,87	76,15	403,85	35,64	-66,12	-30,48	434,33	64,40	41,58	52,25	93,82	158,22
NE	15283	22,96%	289,81	18,31	53,99	72,29	407,71	54,20	-94,04	-39,85	447,55	80,62	51,36	25,76	77,12	157,74
NW	10460	15,71%	307,77	16,06	47,52	63,58	416,42	45,84	-61,25	-15,41	431,83	75,17	28,00	20,89	48,89	124,05
S1	22558	33,89%	249,44	16,30	49,83	66,13	413,87	54,52	-41,42	13,10	400,77	85,85	52,68	12,79	65,47	151,33
S2	7428	11,16%	246,18	20,21	49,48	69,69	410,31	54,15	-46,82	7,33	402,98	91,54	42,55	22,72	65,27	156,81
Totale	**66562**	**100,00%**	**271,85**	**18,46**	**50,71**	**69,17**	**410,83**	**49,97**	**-61,24**	**-11,27**	**422,10**	**80,11**	**45,56**	**24,57**	**70,13**	**150,25**

(a) Results by territories; losses are expressed in minutes.

Territory	# w.d.	% w.d.	OEE	BL_EFB %	BL_S&A %	FL_DW %	A	BL_IMS %	BL_RS %	FL_SP %	NOT %	BL_PD %	BL_RY_susp %	BL_RY_abort %	BL_RY %	FL_DF %
CE	10833	16,3%	57,52	5,06	10,81	15,86	84,14	7,42	-13,77	-6,35	90,49	13,42	8,66	10,88	19,55	32,96
NE	15283	23,0%	60,38	3,81	11,25	15,06	84,94	11,29	-19,59	-8,30	93,24	16,80	10,70	5,37	16,07	32,86
NW	10460	15,7%	64,12	3,35	9,90	13,25	86,75	9,55	-12,76	-3,21	89,96	15,66	5,83	4,35	10,19	25,84
S1	22558	33,9%	51,97	3,40	10,38	13,78	86,22	11,36	-8,63	2,73	83,49	17,89	10,98	2,66	13,64	31,53
S2	7428	11,2%	51,29	4,21	10,31	14,52	85,48	11,28	-9,75	1,53	83,95	19,07	8,86	4,73	13,60	32,67
Totale	**66562**	**100,0%**	**56,64**	**3,85**	**10,57**	**14,41**	**85,59**	**10,41**	**-12,76**	**-2,35**	**87,94**	**16,69**	**9,49**	**5,12**	**14,61**	**31,30**

(b) Results by territories as percentage impact of PPT (PPT View).

TABLE 11. Results by *CC*s in minutes and as percentage of *PPT*. These latter are associated to the PPT view.

Territory / CC	# w.d.	% w.d.	VOT (min)	BL_EFB	BL_S&A	FL_DW	OT (min)	BL_IMS	BL_RS	FL_SP	NOT (min)	BL_PD	BL_RY_susp	BL_RY_abort	BL_RY	FL_DF
CE	**10833**	**16,28%**	**276,11**	**24,28**	**51,87**	**76,15**	**403,85**	**35,64**	**-66,12**	**-30,48**	**434,33**	**64,40**	**41,58**	**52,25**	**93,82**	**158,22**
6628 - Toscana	247	0,37%	289,57	30,11	65,75	95,85	384,15	136,63	-120,86	15,77	368,37	41,49	25,81	11,50	37,31	78,80
6657 - Lazio	4805	7,22%	310,76	11,35	47,68	59,04	420,96	45,15	-65,46	-20,30	441,26	59,53	33,38	37,60	70,98	130,51
6665 - Sardegna	5781	8,69%	246,74	34,77	54,76	89,53	390,47	23,41	-64,32	-40,91	431,39	69,42	49,07	66,16	115,23	184,65
NE	**15283**	**22,96%**	**289,81**	**18,31**	**53,99**	**72,29**	**407,71**	**54,20**	**-94,04**	**-39,85**	**447,55**	**80,62**	**51,36**	**25,76**	**77,12**	**157,74**
6653 - Veneto West	3292	4,95%	291,20	28,33	48,51	76,84	403,16	50,85	-82,47	-31,62	434,78	66,50	55,53	21,55	77,08	143,58
6654 - Veneto North	5455	8,20%	277,43	11,89	56,94	68,83	411,17	57,24	-88,11	-30,88	442,05	83,34	52,69	28,60	81,28	164,62
6656 - Emilia	3436	5,16%	328,31	20,61	55,02	75,64	404,36	47,80	-113,96	-66,17	470,53	78,48	39,53	24,22	63,74	142,22
6681 - Friuli	3100	4,66%	267,46	16,40	53,46	69,86	410,14	59,50	-94,69	-35,19	445,34	93,23	57,70	26,94	84,64	177,87
NW	**10460**	**15,71%**	**307,77**	**16,06**	**47,52**	**63,58**	**416,42**	**45,84**	**-61,25**	**-15,41**	**431,83**	**75,17**	**28,00**	**20,89**	**48,89**	**124,05**
6611 - Piemonte	1665	2,50%	260,00	13,58	48,97	62,55	417,45	66,21	-21,68	44,53	372,92	61,04	30,80	21,08	51,88	112,92
6626 - Milano	3295	4,95%	347,23	12,32	46,81	59,12	420,88	42,85	-69,13	-26,28	447,16	65,92	17,29	16,72	34,01	99,93
6636 - Varese	1997	3,00%	328,28	12,11	45,65	57,77	422,23	44,00	-68,43	-24,44	446,67	86,84	13,97	17,59	31,55	118,39
6646 - Alessandria	1700	2,55%	278,33	22,32	45,42	67,74	412,26	56,07	-75,88	-19,81	432,07	71,90	57,28	24,56	81,84	153,74
6649 - Novara	1803	2,71%	284,82	23,66	51,55	75,21	404,79	24,92	-61,65	-36,74	441,53	95,26	32,90	28,55	61,45	156,71
S1	**22558**	**33,89%**	**249,44**	**16,30**	**49,83**	**66,13**	**413,87**	**54,52**	**-41,42**	**13,10**	**400,77**	**85,85**	**52,68**	**12,79**	**65,47**	**151,33**
6661 - Napoli West	7949	11,94%	231,06	17,21	43,17	60,39	419,61	55,37	-36,45	18,92	400,69	96,36	69,11	4,16	73,27	169,63
6670 - Puglia North	4268	6,41%	254,41	21,56	54,33	75,89	404,11	68,05	-55,87	12,19	391,92	85,89	36,69	14,93	51,62	137,52
6673 - Puglia South	4615	6,93%	267,35	16,92	60,64	77,55	402,45	51,80	-62,27	-10,47	412,91	79,85	38,62	27,10	65,72	145,57
6680 - Campania	5726	8,60%	256,83	10,63	46,99	57,62	422,38	45,44	-20,74	24,71	397,68	76,09	53,12	11,64	64,76	140,85
S2	**7428**	**11,16%**	**246,18**	**20,21**	**49,48**	**69,69**	**410,31**	**54,15**	**-46,82**	**7,33**	**402,98**	**91,54**	**42,55**	**22,72**	**65,27**	**156,81**
6671 - Sicilia West	2865	4,30%	229,23	24,50	53,24	77,74	402,26	64,09	-53,06	11,03	391,24	97,49	42,69	21,82	64,51	162,00
6672 - Sicilia East	4563	6,86%	256,81	17,52	47,12	64,64	415,36	47,91	-42,90	5,00	410,36	87,80	42,46	23,29	65,75	153,55
Totale	**66562**	**100,00%**	**271,85**	**18,46**	**50,71**	**69,17**	**410,83**	**49,97**	**-61,24**	**-11,27**	**422,10**	**80,11**	**45,56**	**24,57**	**70,13**	**150,25**

(a) Results in minutes by the CC.

Territory / CC	# w.d.	% w.d.	OEE	BL_EFB %	BL_S&A %	FL_DW %	A	BL_IMS %	BL_RS %	FL_SP %	NOT %	BL_PD %	BL_RY_susp %	BL_RY_abort %	BL_RY %	FL_DF %
CE	**10833**	**16,3%**	**57,52**	**5,06**	**10,81**	**15,86**	**84,14**	**7,42**	**-13,77**	**-6,35**	**90,49**	**13,42**	**8,66**	**10,88**	**19,55**	**32,96**
6628 - Toscana	247	0,4%	60,33	6,27	13,70	19,97	80,03	28,46	-25,18	3,29	76,74	8,64	5,38	2,40	7,77	16,42
6657 - Lazio	4805	7,2%	64,74	2,37	9,93	12,30	87,70	9,41	-13,64	-4,23	91,93	12,40	6,95	7,83	14,79	27,19
6665 - Sardegna	5781	8,7%	51,40	7,24	11,41	18,65	81,35	4,88	-13,40	-8,52	89,87	14,46	10,22	13,78	24,01	38,47
NE	**15283**	**23,0%**	**60,38**	**3,81**	**11,25**	**15,06**	**84,94**	**11,29**	**-19,59**	**-8,30**	**93,24**	**16,80**	**10,70**	**5,37**	**16,07**	**32,86**
6653 - Veneto West	3292	4,9%	60,67	5,90	10,11	16,01	83,99	10,59	-17,18	-6,59	90,58	13,85	11,57	4,49	16,06	29,91
6654 - Veneto North	5455	8,2%	57,80	2,48	11,86	14,34	85,66	11,92	-18,36	-6,43	92,09	17,36	10,98	5,96	16,93	34,30
6656 - Emilia	3436	5,2%	68,40	4,29	11,46	15,76	84,24	9,96	-23,74	-13,78	98,03	16,35	8,23	5,05	13,28	29,63
6681 - Friuli	3100	4,7%	55,72	3,42	11,14	14,55	85,45	12,40	-19,73	-7,33	92,78	19,42	12,02	5,61	17,63	37,06
NW	**10460**	**15,7%**	**64,12**	**3,35**	**9,90**	**13,25**	**86,75**	**9,55**	**-12,76**	**-3,21**	**89,96**	**15,66**	**5,83**	**4,35**	**10,19**	**25,84**
6611 - Piemonte	1665	2,5%	54,17	2,83	10,20	13,03	86,97	13,79	-4,52	9,28	77,69	12,72	6,42	4,39	10,81	23,52
6626 - Milano	3295	5,0%	72,34	2,57	9,75	12,32	87,68	8,93	-14,40	-5,48	93,16	13,73	3,60	3,48	7,09	20,82
6636 - Varese	1997	3,0%	68,39	2,52	9,51	12,04	87,96	9,17	-14,26	-5,09	93,06	18,09	2,91	3,66	6,57	24,66
6646 - Alessandria	1700	2,6%	57,99	4,65	9,46	14,11	85,89	11,68	-15,81	-4,13	90,02	14,98	11,93	5,12	17,05	32,03
6649 - Novara	1803	2,7%	59,34	4,93	10,74	15,67	84,33	5,19	-12,84	-7,65	91,99	19,85	6,85	5,95	12,80	32,65
S1	**22558**	**33,9%**	**51,97**	**3,40**	**10,38**	**13,78**	**86,22**	**11,36**	**-8,63**	**2,73**	**83,49**	**17,89**	**10,98**	**2,66**	**13,64**	**31,53**
6661 - Napoli West	7949	11,9%	48,14	3,59	8,99	12,58	87,42	11,54	-7,59	3,94	83,48	20,07	14,40	0,87	15,27	35,34
6670 - Puglia North	4268	6,4%	53,00	4,49	11,32	15,81	84,19	14,18	-11,64	2,54	81,65	17,89	7,64	3,11	10,76	28,65
6673 - Puglia South	4615	6,9%	55,70	3,52	12,63	16,16	83,84	10,79	-12,97	-2,18	86,02	16,63	8,05	5,65	13,69	30,33
6680 - Campania	5726	8,6%	53,51	2,21	9,79	12,00	88,00	9,47	-4,32	5,15	82,85	15,85	11,07	2,43	13,49	29,34
S2	**7428**	**11,2%**	**51,29**	**4,21**	**10,31**	**14,52**	**85,48**	**11,28**	**-9,75**	**1,53**	**83,95**	**19,07**	**8,86**	**4,73**	**13,60**	**32,67**
6671 - Sicilia West	2865	4,3%	47,76	5,10	11,09	16,20	83,80	13,35	-11,05	2,30	81,51	20,31	8,89	4,55	13,44	33,75
6672 - Sicilia East	4563	6,9%	53,50	3,65	9,82	13,47	86,53	9,98	-8,94	1,04	85,49	18,29	8,85	4,85	13,70	31,99
Totale	**66562**	**100,0%**	**56,64**	**3,85**	**10,57**	**14,41**	**85,59**	**10,41**	**-12,76**	**-2,35**	**87,94**	**16,69**	**9,49**	**5,12**	**14,61**	**31,30**

(b) Results by the CCs as percentage impact of PPT (PPT View).

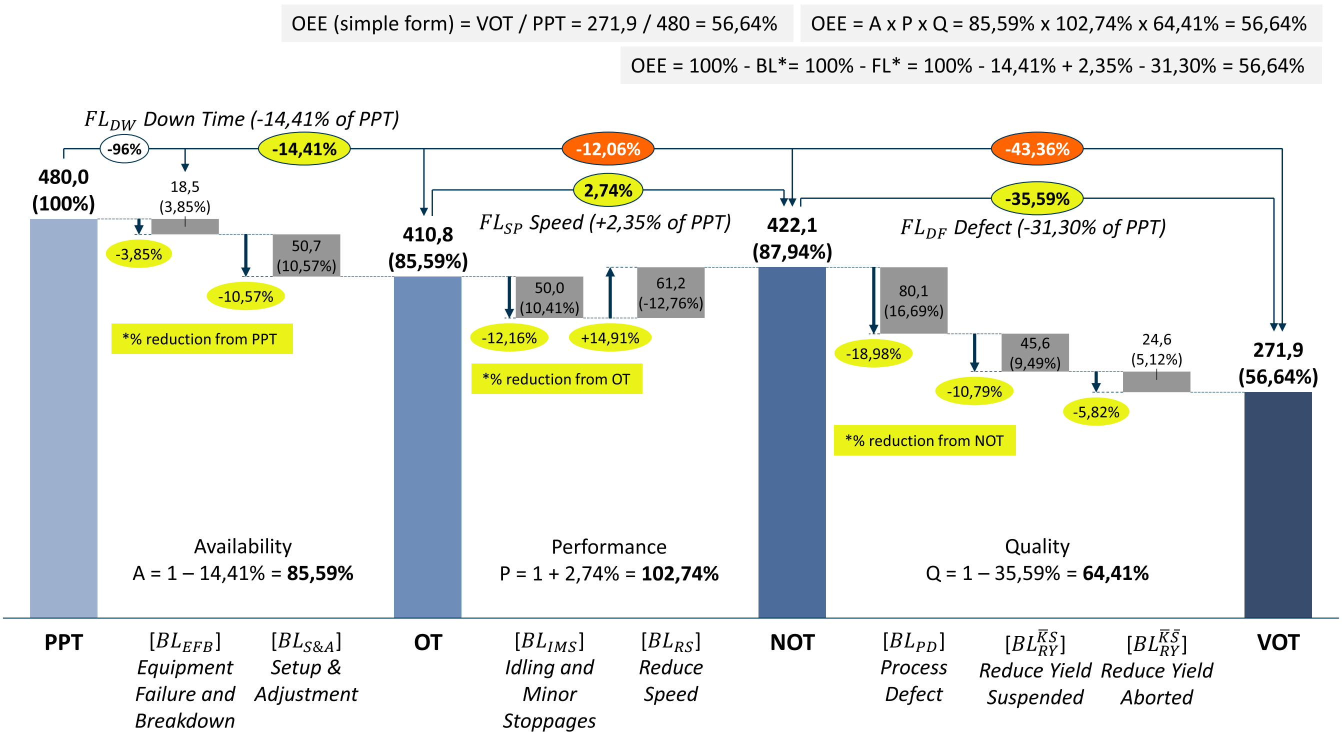


FIGURE 15. The graph shows the *OEE* results by comparing the representation of the parameters and factors, and the weight of each loss respect to the *PPT*.

- alternatively, as a function of the total loss expressed as the 3 families of losses: $100\% - \mathbf{FL}_*$;
- as the product of the 3 factors, i.e., $A \cdot P \cdot Q$.

2) RESULTS BY TERRITORY

Table 12 shows all parameters and factors comparing the results among the territories. These results address the question **Q2** stated in the introduction, which is related to the impact of territorial peculiarities on efficiency.

The relevant losses to consider are BL_{EFB} and $BL_{S\&A}$, since they refer to the impact of the territory on the activities. The two losses are related, respectively, to the organization of the company in the territory and the geographical peculiarities that affect the activities. This summary table shows the value of **BL**, the 3 factors and *OEE* for the 5 territories. The table identifies problems and strengths and the reasons that determine the final value of the *OEE* for each territory. In particular:

- The *NW* territory has the highest *OEE* value (64.12%); its strong point is a high value for *Q* (71.21%).
- The second territory by *OEE* value is the *NE* (60.38%). *P* is very high (109.77%), but unfortunately *Q* has a low value (64.76%) due to a high number of suspended activities.
- The third territory is *CE*. It has a good value of *P* (107.55%), thanks to the low value of *A* (84.14%). Its weak point is *Q*, due to a high number of aborted activities.
- For *S1* and *S2* territories, the results show problems with a low *P* and *Q* values due to a high number of completed but non-compliant activities.

3) RESULTS BY COST CENTER

Table 13 shows all the parameters and the factors comparing the results among the *CC*s. As for the territories, these results also address question **Q2**.

This summary table shows the value of **BL**, the 3 factors and *OEE* for the 18 *CC*s. This table identifies problems and strengths, and the reasons that determine the final value of the *OEE* for each *CC*s. *CC*s, belonging to the same territory and with comparable *OEE* values, have different problems:

- The 5 *CC*s belonging to the *NW* territory have different outcomes: 6611 has low *P*, other 6626 and 6636 have a very high *Q*.
- The 4 *CC*s belonging to the *NE* territory have good *P* but each *CC* exhibits different types of problems on *Q*, related to the problems in completing the activities or on their compliance.
- The 3 *CC*s belonging to the *CE* territory also show different outcomes. In detail, 6665 and 6628 suffer a low *A*. 6628 has good *Q* but a low *P*; otherwise 6665 has good *P* but poor *Q* due to a high number of aborted activities.
- The 6 *CC*s belonging to *S1* and *S2* territories, have a low *OEE* value. The values of *P* are low due to a longer *OCT*s to perform the activities. Despite longer *OCT*s, *Q* poses a problem, mainly due to the high number of completed but non-compliant activities.

TABLE 12. The table reports the *OEE* result by the territories.

Territory	OEE	BL_EFB	BL_S&A	FL_DW	A	BL_IMS	BL_RS	FL_SP	P	BL_PD	BL_RY_susp	BL_RY_abort	BL_RY	FL_DF	Q
CE	57,52	5,058	10,806	15,864	84,14	8,82	-16,37	-7,55	107,55	14,826	9,57	12,03	21,60	36,43	63,57
NE	60,38	3,814	11,247	15,061	84,94	13,29	-23,07	-9,77	109,77	18,014	11,48	5,76	17,23	35,24	64,76
NW	64,12	3,346	9,901	13,246	86,75	11,01	-14,71	-3,70	103,70	17,407	6,48	4,84	11,32	28,73	71,27
S1	51,97	3,396	10,381	13,777	86,22	13,17	-10,01	3,17	96,83	21,422	13,15	3,19	16,34	37,76	62,24
S2	51,29	4,211	10,308	14,519	85,48	13,20	-11,41	1,79	98,21	22,714	10,56	5,64	16,20	38,91	61,09
Totale	**56,64**	**3,846**	**10,565**	**14,411**	**85,59**	**12,16**	**-14,91**	**-2,74**	**102,74**	**18,980**	**10,79**	**5,82**	**16,61**	**35,59**	**64,41**

TABLE 13. The table reports the *OEE* result by the *CC*.

Territory / CC	OEE	BL_EFB	BL_S&A	FL_DW	A	BL_IMS	BL_RS	FL_SP	P	BL_PD	BL_RY_susp	BL_RY_abort	BL_RY	FL_DF	Q
CE	**57,52**	**5,058**	**10,806**	**15,864**	**84,14**	**8,82**	**-16,37**	**-7,55**	**107,55**	**14,826**	**9,57**	**12,03**	**21,60**	**36,43**	**63,57**
6628 - Toscana	60,33	6,272	13,698	19,970	80,03	35,57	-31,46	4,11	95,89	11,263	7,01	3,12	10,13	21,39	78,61
6657 - Lazio	64,74	2,365	9,934	12,300	87,70	10,73	-15,55	-4,82	104,82	13,491	7,56	8,52	16,08	29,58	70,42
6665 - Sardegna	51,40	7,244	11,407	18,651	81,35	6,00	-16,47	-10,48	110,48	16,092	11,37	15,34	26,71	42,80	57,20
NE	**60,38**	**3,814**	**11,247**	**15,061**	**84,94**	**13,29**	**-23,07**	**-9,77**	**109,77**	**18,014**	**11,48**	**5,76**	**17,23**	**35,24**	**64,76**
6653 - Veneto West	60,67	5,903	10,106	16,008	83,99	12,61	-20,46	-7,84	107,84	15,294	12,77	4,96	17,73	33,02	66,98
6654 - Veneto North	57,80	2,477	11,862	14,339	85,66	13,92	-21,43	-7,51	107,51	18,852	11,92	6,47	18,39	37,24	62,76
6656 - Emilia	68,40	4,294	11,463	15,758	84,24	11,82	-28,18	-16,36	116,36	16,678	8,40	5,15	13,55	30,23	69,77
6681 - Friuli	55,72	3,417	11,137	14,554	85,45	14,51	-23,09	-8,58	108,58	20,934	12,96	6,05	19,01	39,94	60,06
NW	**64,12**	**3,346**	**9,901**	**13,246**	**86,75**	**11,01**	**-14,71**	**-3,70**	**103,70**	**17,407**	**6,48**	**4,84**	**11,32**	**28,73**	**71,27**
6611 - Piemonte	54,17	2,830	10,203	13,032	86,97	15,86	-5,19	10,67	89,33	16,368	8,26	5,65	13,91	30,28	69,72
6626 - Milano	72,34	2,566	9,752	12,317	87,68	10,18	-16,43	-6,24	106,24	14,742	3,87	3,74	7,61	22,35	77,65
6636 - Varese	68,39	2,524	9,511	12,035	87,96	10,42	-16,21	-5,79	105,79	19,441	3,13	3,94	7,06	26,50	73,50
6646 - Alessandria	57,99	4,650	9,462	14,112	85,89	13,60	-18,40	-4,81	104,81	16,641	13,26	5,68	18,94	35,58	64,42
6649 - Novara	59,34	4,929	10,739	15,668	84,33	6,16	-15,23	-9,08	109,08	21,575	7,45	6,47	13,92	35,49	64,51
S1	**51,97**	**3,396**	**10,381**	**13,777**	**86,22**	**13,17**	**-10,01**	**3,17**	**96,83**	**21,422**	**13,15**	**3,19**	**16,34**	**37,76**	**62,24**
6661 - Napoli West	48,14	3,586	8,995	12,581	87,42	13,20	-8,69	4,51	95,49	24,047	17,25	1,04	18,29	42,33	57,67
6670 - Puglia North	53,00	4,491	11,319	15,810	84,19	16,84	-13,82	3,02	96,98	21,916	9,36	3,81	13,17	35,09	64,91
6673 - Puglia South	55,70	3,524	12,633	16,157	83,84	12,87	-15,47	-2,60	102,60	19,338	9,35	6,56	15,92	35,25	64,75
6680 - Campania	53,51	2,214	9,789	12,003	88,00	10,76	-4,91	5,85	94,15	19,133	13,36	2,93	16,29	35,42	64,58
S2	**51,29**	**4,211**	**10,308**	**14,519**	**85,48**	**13,20**	**-11,41**	**1,79**	**98,21**	**22,714**	**10,56**	**5,64**	**16,20**	**38,91**	**61,09**
6671 - Sicilia West	47,76	5,104	11,091	16,195	83,80	15,93	-13,19	2,74	97,26	24,919	10,91	5,58	16,49	41,41	58,59
6672 - Sicilia East	53,50	3,650	9,816	13,466	86,53	11,53	-10,33	1,20	98,80	21,395	10,35	5,68	16,02	37,42	62,58
Totale	**56,64**	**3,846**	**10,565**	**14,411**	**85,59**	**12,16**	**-14,91**	**-2,74**	**102,74**	**18,980**	**10,79**	**5,82**	**16,61**	**35,59**	**64,41**

C. RESULTS BY SPECIALIZED OPERATOR

The *OEE* framework allows a precise evaluation of all the parameters for each *SO*. This evaluation addresses question **Q3** stated in the introduction.

By associating the first 2 big losses correlated to the Availability (BL_{EFB} and $BL_{S\&A}$), with the losses attributable to the company, the Operating Time (OT) is obtained, which is the available time for each *SO* to perform the activities in each working day.

The value of P for each *SO* is calculated considering the net available time (NOT/OT) and not with respect to the entire duration of the working day (PPT). This means that the value of P for the *SO*s can be compared as they are normalized with respect to the OT. For example, the P of a *SO* working in an area where travel times are long can be compared with a *SO* working in an urban area.

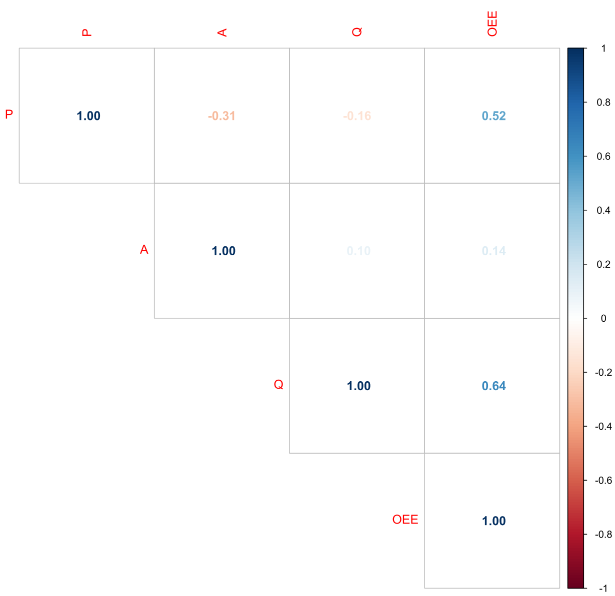
Figure 16 shows the results for 952 *SO*s; Q and P values are on X- and Y-axis, respectively. The color intensity is related to the *OEE* value, which depends on P and Q, but also on A. Clearly, the *OEE* value grows moving from the lower left corner, where P and Q are low, to the upper right corner with high P and Q. In practice, the graph is the representation, for each *SO*, of his position with respect to the rest of the population of *SO*s. This graph allows to objectively compare the *SO*s, having excluded from the result the component related to the company, the territory and its organization, which are all elements related to the Availability. The graph also shows level density curves, which allows identifying an agglomeration point for $Q \approx 62.5$ and $P \approx 100$.

D. DISCUSSION ON THE CORRELATIONS AMONG ALL THE PARAMETERS

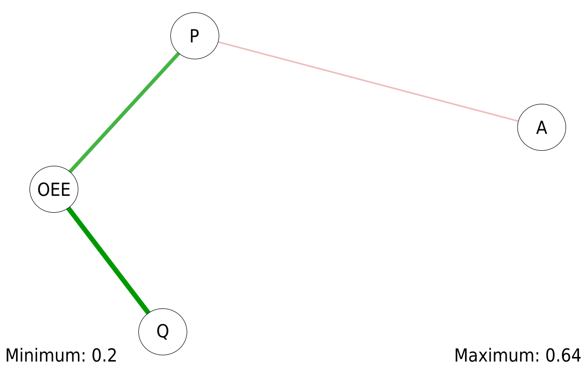
This section discusses the correlation between the Big Losses, the 3 factors and the *OEE* value. We also want to show how the structure of the *OEE* framework manages to generate a correct correlation between the factors, providing the holistic view that is necessary for the correct understanding of the phenomenon with the final objective of selecting corrective actions to increase performance. This is the answer the question **Q4**.

The correlation matrix and the correlation network are two tools for evaluating the relationship between variables [36], [37]. The correlation matrix is meant for visual exploration. It helps in the detection of hidden patterns among variables. The correlation network provides a useful visual picture of the correlations. In a correlation network, the relative thickness and color density of the bands indicate the strength of Pearson coefficients. The color of each band indicates a positive or negative correlation: red for negative and green for positive. Typically, it also provides p-values and confidence intervals to help users determine the statistical significance of the correlations.

FIGURE 16. ***Q* vs. *P* and *OEE* value for 952 *SOs*.**



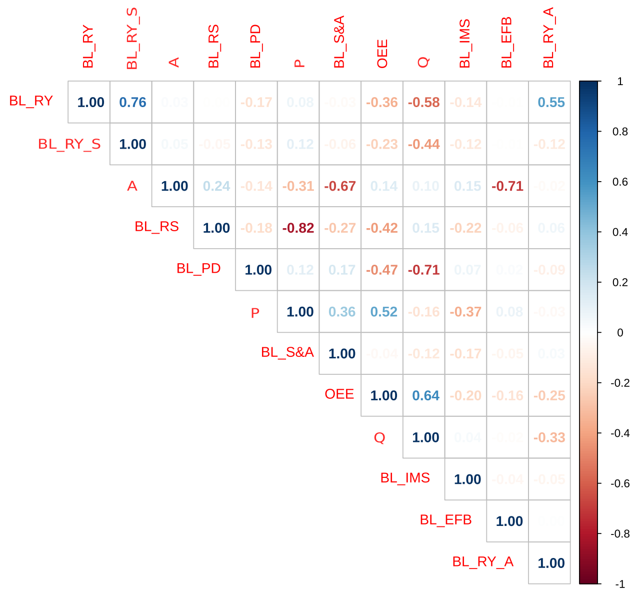
(a) Correlation matrix among A, P, Q and OEE.



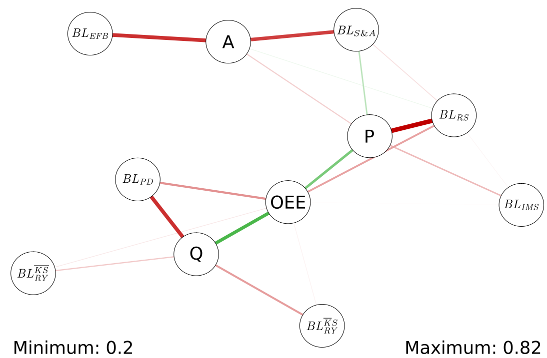
(b) Network correlation among A, P, Q and OEE.

FIGURE 17. **Network and matrix correlation among *A*, *P*, *Q* and *OEE*.**

In the derivation of the correlation network, we set $\alpha = 0.05$ as the limit in the visualization of the correlation bands.



(a) Correlation matrix among A, P, Q, $\mathbf{BL}$ and OEE.



(b) Network correlation among A, P, Q, $\mathbf{BL}$ and OEE.

FIGURE 18. **Network and matrix correlation among *A*, *P*, *Q*, BL and *OEE*. The reported values refer to the OEE view. Therefore, the values are calculated with reference to the OEE View framework.**

Figures 18a and 18b show a strong direct correlation between P and OEE, equal to $+0.52$, and between Q and OEE, equal to $+0.64$. This confirms that as P and Q increase, the value of OEE increases as well.

There is no correlation between A and OEE ($+0.14$). This can be explained as an increase in available time does not directly translate into an increase in the OEE. Indeed, there is an inverse correlation between A and P, equal to -0.31. This shows that the increase in available time is not used to perform an extra expected activity. The extra available time only increases the OT value. Keeping the NOT value constant involves a decrease of P.

In a further evaluation, the losses are added to the correlation analysis.

The strong inverse relationships between the $\mathbf{BL}$ and the 3 factors is due to the OEE framework structure. Hence, we have the following inverse relationships:

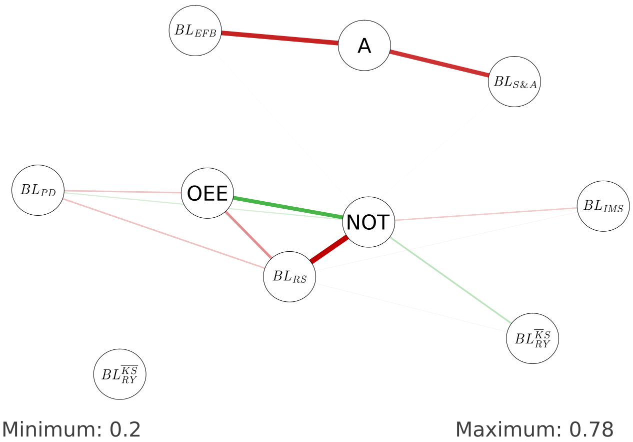


FIGURE 19. Network correlation among ***A***, ***NOT***, **BL** and ***OEE*** as percentage of ***PPT***. The reported values thus refer to the PPT view. Therefore, the values are calculated with reference to the PPT View framework.

- For BL_{EFB}, $BL_{S\&A}$ and A the correlation values are respectively, -0.71 and -0.67.
- For BL_{IMS}, BL_{RS} and P the correlation values are respectively, -0.71 and -0.67.
- For BL_{PD}, $BL_{RY}^{\overline{K}S}$, $BL_{RY}^{\overline{KS}}$ and Q the correlation values are respectively, -0.71, -0.44 and -0.33. The correlation between BL_{RY} and Q is equal to -0.58.

The remaining relationships are particularly interesting to analyze. The inverse correlation between A and P is related to the inverse correlation between $BL_{S\&A}$ and BL_{RS}, equal to -0.27. The first is motivated by the OPEs tracking method of the process described in Figure 8. This also arises in the correlation between BL_{IMS} and BL_{RS}, equal to -0.22. An incorrect declaration of the end of the travel that happens before the actual ending implies a longer duration of the subsequent activity, and vice-versa. This previous relationship also motivates the lower inverse relationship between BL_{IMS} and P, despite the impact of BL_{IMS} being considered in terms of percentage compared to PPT. Hence, the increase in BL_{IMS} is partially offset by the reduction in BL_{RS}.

The second effect is that the more time available does not translate into an extra performed activity. It is interesting, once again, that there are no relations between BL_{IMS} and OEE, and between BL_{EFB} and $BL_{S\&A}$ and OEE. As a result, the extra time available does not directly translate into better final performance.

BL_{RS} is certainly one of the parameters that most affect the OEE. Performing simple activities requiring less time than expected, leads to greater productivity.

There are strong inverse correlations between the BL_{PD}, the BL_{RY} and the OEE, respectively equal to -0.47 and -0.36. There are inverse correlations also between the two losses of the BL_{RY}, $BL_{RY}^{\overline{K}S}$ and $BL_{RY}^{\overline{KS}}$, and OEE; the values are respectively -0.23 and -0.25. This confirms the impact of having a poor Quality on the overall performance. It is important to observe the independence of Q and its losses from A, P and the corresponding 4 losses.

As explained below, it is questionable whether these pieces of evidence would be visible without leveraging the OEE framework.

In Figure 19, we consider all the losses in a percentage value with respect to PPT (PPT View). In the figure, we can highlight the following fundamental aspects:

- The relation between A and P (which is equal to NOT according to the above considerations) and their 4 losses are lost.
- A and its losses appear to be irrelevant to the OEE value.
- The problem of poor Quality appears less evident w.r.t. the use of the whole OEE framework.
- The OEE value is completely determined by the productivity value NOT.
- Having losses in Q, due to suspension of activities ($BL_{RY}^{\overline{K}S}$) and completed non-compliant activities (BL_{RY}), seems to be a benefit, because they increase the value of NOT.

In conclusion, the comparison of the two views shows the incorrect reading of the **BL**, when it is done by using PPT View. In fact, the PPT View:

- does not allow a holistic view of the OEE framework to understand the situation;
- does not highlight the correct relationships, and indeed
- could lead to incorrect interpretation of the phenomena and possibly wrong actions to solve the problems.

E. COMPLETION AND COMPLIANCE

This section presents an evaluation of completion and compliance of activities. The observations reported in this section address and quantify a hidden efficiency bottleneck that is part of the answer to question **Q1**.

Since the value of NOT is composed of VOT and the losses related to Q, we start by decomposing the NOT value into 4 components. According to the classification explained in Table 5 and Figure 4, there are 4 possible states of closure of activities:

1) completed and compliant activities; they determine the VOT.
2) completed and non-compliant activities; they correspond to $BL_{PD}^{K\overline{C}}$.
3) uncompleted and suspended activities ($BL_{RY}^{\overline{K}S}$).
4) uncompleted and aborted activities ($BL_{RY}^{\overline{KS}}$).

By definition, the NOT is the overall time used to perform useful work. This time is the sum of the ECTs of the activities. The NOT without the two losses belonging to Defect Family Losses is equal to the VOT (Eq. (14)); VOT divided by PPT corresponds to the OEE (Eq. (2)), while VOT divided by NOT is equal to Q (Eq. (17)).

Therefore, it is possible to determine the percentage impact of each loss that belongs to FL_{DF}, which is the family loss related to Q, with respect to the NOT. Q corresponds to the difference between 100% (the NOT) and the percentage impacts of the losses (Eq. (17)). The relevant values related

TABLE 14. Relevant values related to *Q* for the whole workforce; results are reported in terms of number of activities and *ECT*s.

C_QualityState_Complete	n.Activities	%Act.	ECT (minutes)	% time
complete	**365886**	**77,05%**	**23427746**	**83,39%**
compliance	**294700**	**62,06%**	**18095136**	**64,41%**
Complete	294700	✓ 62,06%	18095136	✓ 64,41%
non_compliance	**71186**	**14,99%**	**5332610**	**18,98%**
Complete	71186	✗ 14,99%	5332610	✗ 18,98%
not_complete	**108963**	**22,95%**	**4668094**	**16,61%**
non_compliance	**108963**	**22,95%**	**4668094**	**16,61%**
Aborted	43784	✗ 9,22%	1635489	✗ 5,82%
Suspended	65179	✗ 13,73%	3032605	✗ 10,79%
Total	**474849**	**100,00%**	**28095840**	**100,00%**

to Q for the whole workforce are shown in Table 14. Results are reported in the table in terms of a number of activities and ECTs.

It can be observed that the percentage ECT of completed activities is greater than the percentage number of completed activities. This is because, for uncompleted activities, the value of OCT is used instead of ECT to improve the accuracy of the calculations; as already motivated in Section VI-D, the OCT for uncompleted activities is often lower than ECT, due to suspensions and abortions.

From the results of the number of activities in Table 14, it is possible to conclude that:

- 62.06% of activities are completed and compliant. The sum of the ECTs of these activities corresponds to 64.41% of the NOT; this time is equal to the VOT.
- 37.94% of activities are non-compliant; it corresponds to 35.59% of the NOT. The non-compliant activities are further characterized as follows:
  - 14.99% of activities are completed; the loss $BL_{PD}^{K\overline{C}}$ is 18.98% of the NOT.
  - 13.73% of activities are suspended; the loss $BL_{RY}^{\overline{K}S}$ is 10.79% of the NOT.
  - 9.22% of activities are aborted; the loss $BL_{RY}^{\overline{KS}}$ is 5.82% of NOT.

The result presented in this section allows looking at $BL_{S\&A}$, the loss related to travels, differently. Since 37.94% of the worked activities are non-compliant, which means that there have been up to 37.94% of travels that did not lead to some useful work. This is an approximation due to the calculation of the best path that has been done in the case of non-compliant activities, since it is not possible to exactly calculate the overall best travel path by excluding the non-compliant activities. However, the data provides an indication of the extent of the problem. SOs traveled up to about 61% (37.94/62.06) more than what would have been required in case of the absence of non-compliant activities. This corresponds to an average of 19.24 minutes per working day, equal to 4% of the PPT. It is worth outlining that "lost travels" have associated costs, e.g., vehicle usage, fuel, etc. whose estimation is beyond the scope of this paper.

X. LIMITATIONS

The reliability of the results provided by the proposed framework depends on the quality and the volume of the collected data. To achieve high data quality, a periodic assessment of the quality is required. Therefore, important economic investments and rigorous procedures may be necessary for an effective application of the framework [12]. For these reasons, the framework is recommended for medium to large service companies.

Another limitation of the proposed framework is that it is suited on service companies whose employees are required to travel across the territory, as specified in the assumptions of the framework itself listed in Section V.

Finally, the framework has been tested on one single service company, although very representative of the type of company that could benefit from the insights derived by the application of the framework. Further testing may confirm the applicability and usefulness of the framework.

XI. CONCLUSION

In this paper, the OEE framework has been revised and adapted for its application to a service company. Every loss and parameter has been described in detail, in compliance with rules and principles of the adapted framework in order to obtain the correct measurements. The framework was applied to the case study of an Italian service company with about 1000 Specialized Operators (SOs) who travel across the country for interventions in telecommunication networks.

The obtained results answer to the questions presented in Section I. In particular:

- **Q1**: The application of our framework provides objective and clear measures of the 3 factors and the losses, which allow identifying the source of efficiency bottlenecks; this was done in Section V by carefully characterizing the various losses for a service company in the context of the OEE framework.
- **Q2**: The framework distinguishes between the losses attributable to the company and the SO (Table 4). The former are associated with the territory. Our framework allows us to group the information regarding the SO's working days by geographical area. This enables to perform statistical analyses on the A factor, which is related to the company, in different areas. For the case study, the results for different geographic territories and CCs are assessed in Section IX-B. It is interesting to note that the application of the proposed framework, thanks to the results related to the Availability factor, may contribute to addressing some Environmental, Social and Governance (ESG) aspects [38]. Availability is the measure of the *effectiveness* of doing the necessary things, defining the correct priorities and, at the same time, the *efficiency* in carrying them out. The Availability is a measure of both travels and service activities. Once the measure is done, it is possible to identify the most efficient and effective areas within the organization and develop the

best practices that can be extended to the entire company, with benefits to the governance. Moreover, the optimization of travels can reduce the emissions associated with the activities of the company.

- **Q3**: Inefficiencies related to business organization impact only on Availability, while the inefficiencies related to the *SO*s have an impact on Performance and Quality. The assessment of the losses in detail enables the comparison of different *SO*s among different areas, which are represented by territories or *CC*s in the case study (Section IX-C).
- **Q4**: The *OEE* framework allows the examination the overall results of a production unit (the *SO*), of an area or the entire company by considering all the working days, each one with its *PPT*. The holistic aspect of the process is achieved through the processing of many working days (more than 66, 000, in the case study). Using a such large amount of data, it is possible both to identify the individual causes of the inefficiency and to correlate the losses, the factors and the *OEE* value. The coefficients are in fact correlated and it is possible to show how the variation of each one affects the others. Our proposed analysis is also compared with a network correlation of the losses and coefficients, developed in Section IX-D. It is observed that, not only the results are substantially different, but in the network correlation approach the conclusions are also incorrect. The values of the losses are considered not only with respect to the time, or with respect to the *PPT* (PPT View), but with respect to the relative net time available, with reference to the *OEE* framework (OEE View).
- **Q5**: The use of the *OCT* instead of the *ECT* for suspended and aborted activities, as described in Section VI-H, allows a more accurate calculation of the various factors w.r.t. the typical application of the standard *OEE* framework.

In conclusion, a valid framework has been obtained that allows assessing the performance of the company, in order to possibly plan actions for improving productivity, and quantitatively evaluate the extent of the improvement.

REFERENCES

[1] A. Cifalinò, *Misurazione Delle Performance Aziendali e Valutazione Della Formazione*. Milan, Italy: Franco Angeli, 2012, pp. 1–208.

[2] A. Neely, C. Adams, and P. Crowe, ''The performance prism in practice,'' *Measuring Bus. Excellence*, vol. 5, pp. 6–13, Jun. 2001.

[3] M. Bellgran and E. K. Säfsten, *Production Development: Design and Operation of Production Systems*. London, U.K.: Springer, 2009.

[4] Y. Jabareen, ''Building a conceptual framework: Philosophy, definitions, and procedure,'' *Int. J. Qualitative Methods*, vol. 8, no. 4, pp. 49–62, Dec. 2009.

[5] S. Nakajima, *Introduction to TPM: Total Productive Maintenance* (Preventative Maintenance Series). New York, NY, USA: Productivity Press, 1988.

[6] L. D. C. Ng Corrales, M. P. Lambán, M. E. H. Korner, and J. Royo, ''Overall equipment effectiveness: Systematic literature review and overview of different approaches,'' *Appl. Sci.*, vol. 10, no. 18, p. 6469, Sep. 2020.

[7] A. Sohal, J. Olhager, P. O'Neill, and D. Prajogo, ''Implementation of OEE–issues and challenges,'' in *Proc. Int. Conf. Adv. Prod. Manag. Syst. (APMS)*, Cernobbio, Italy, 2010, pp. 1–8.

[8] R. K. Kennedy, *Understanding, Measuring, and Improving Overall Equipment Effectiveness: How to Use OEE to Drive Significant Process Improvement*. New York, NY, USA: Taylor & Francis, 2017.

[9] C. Andersson and M. Bellgran, ''Combining overall equipment efficiency (OEE) and productivity measures as drivers for production improvements,'' in *Proc. 4th Swedish Prod. Symp. (SPS)*, 2011, pp. 3–5.

[10] S. G. da Costa and E. P. de Lima, ''Uses and misuses of the 'overall equipment effectiveness' for production management,'' in *Proc. IEEE Int. Eng. Manag. Conf.*, vol. 2, Aug. 2002, pp. 816–820.

[11] P. De Groote, ''Maintenance performance analysis: A practical approach,'' *J. Quality Maintenance Eng.*, vol. 1, no. 2, pp. 4–24, Jun. 1995.

[12] Õ. Ljungberg, ''Measurement of overall equipment effectiveness as a basis for TPM activities,'' *Int. J. Oper. Prod. Manag.*, vol. 18, no. 5, pp. 495–507, May 1998.

[13] D. Kotze, ''Consistency, accuracy lead to maximum OEE benefits,'' *TPM Newslett.*, vol. 4, no. 2, pp. 1–4, 1993.

[14] D. H. Stamatis, *The OEE Primer: Understanding Overall Equipment Effectiveness, Reliability, and Maintainability*. Boca Raton, FL, USA: CRC Press, 2017.

[15] K. Jeong and D. T. Phillips, ''Operational efficiency and effectiveness measurement,'' *Int. J. Oper. Prod. Manag.*, vol. 21, no. 11, pp. 1404–1416, Nov. 2001.

[16] G. Waeyenbergh and L. Pintelon, ''A framework for maintenance concept development,'' *Int. J. Prod. Econ.*, vol. 77, no. 3, pp. 299–313, Jun. 2002.

[17] J. García-Arca, J. C. Prado-Prado, and A. J. Fernández-González, ''Integrating KPIs for improving efficiency in road transport,'' *Int. J. Phys. Distrib. Logistics Manag.*, vol. 48, no. 9, pp. 931–951, Sep. 2018.

[18] A. Muñoz-Villamizar, J. Santos, J. R. Montoya-Torres, and C. Jaca, ''Using OEE to evaluate the effectiveness of urban freight transportation systems: A case study,'' *Int. J. Prod. Econ.*, vol. 197, pp. 232–242, Mar. 2018.

[19] P. Achanga, E. Shehab, R. Roy, and G. Nelder, ''Critical success factors for lean implementation within SMEs,'' *J. Manuf. Technol. Manag.*, vol. 17, no. 4, pp. 460–471, Jun. 2006.

[20] M. M. O. Pinto, D. J. K. Goldberg, and J. S. L. Cardoso, ''Benchmarking operational efficiency of port terminals using the OEE indicator,'' *Maritime Econ. Logistics*, vol. 19, no. 3, pp. 504–517, Aug. 2017.

[21] A. C. Herrero, J. A. Sanguesa, F. J. Martinez, P. Garrido, and C. T. Calafate, ''Mitigating electromagnetic noise when using low-cost devices in industry 4.0,'' *IEEE Access*, vol. 9, pp. 63267–63282, 2021.

[22] P. Muchiri and L. Pintelon, ''Performance measurement using overall equipment effectiveness (OEE): Literature review and practical application discussion,'' *Int. J. Prod. Res.*, vol. 46, no. 13, pp. 3517–3535, Jul. 2008.

[23] I. Ivancic, ''Development of maintenance in modern production,'' in *Proc. Euromaintenance Conf.* Dubrovnik, Croatia: CRO, 1998, pp. 5–7.

[24] A. Raouf, ''Improving capital productivity through maintenance,'' *Int. J. Oper. Prod. Manag.*, vol. 14, no. 7, pp. 44–52, Jul. 1994.

[25] M. Braglia, M. Frosolini, and F. Zammori, ''Overall equipment effectiveness of a manufacturing line (OEEML),'' *J. Manuf. Technol. Manag.*, vol. 20, no. 1, pp. 8–29, Dec. 2008.

[26] R. Domingo and S. Aguado, ''Overall environmental equipment effectiveness as a metric of a lean and green manufacturing system,'' *Sustainability*, vol. 7, no. 7, pp. 9031–9047, Jul. 2015.

[27] J. A. Garza-Reyes, ''From measuring overall equipment effectiveness (OEE) to overall resource effectiveness (ORE),'' *J. Qual. Maintenance Eng.*, vol. 21, no. 4, pp. 506–527, Oct. 2015.

[28] P. Jonsson and M. Lesshammar, ''Evaluation and improvement of manufacturing performance measurement systems—The role of OEE,'' *Int. J. Oper. Prod. Manag.*, vol. 19, no. 1, pp. 55–78, Jan. 1999.

[29] R. M. Nachiappan and N. Anantharaman, ''Evaluation of overall line effectiveness (OLE) in a continuous product line manufacturing system,'' *J. Manuf. Technol. Manag.*, vol. 17, no. 7, pp. 987–1008, Oct. 2006.

[30] P. Nelson Raja, S. Kannan, and V. Jeyabalan, ''Overall line effectiveness—A performance evaluation index of a manufacturing system,'' *Int. J. Productiv. Qual. Manag.*, vol. 5, no. 1, pp. 38–59, 2010.

[31] M. Braglia, R. Gabbrielli, and L. Marrazzini, ''Overall task effectiveness: A new lean performance indicator in engineer-to-order environment,'' *Int. J. Productiv. Perform. Manag.*, vol. 68, no. 2, pp. 407–422, Feb. 2019.

[32] J. Maleyeff, E. A. Arnheiter, and V. Venkateswaran, ''The continuing evolution of lean six sigma,'' *TQM J.*, vol. 24, no. 6, pp. 542–555, Sep. 2012.
[33] S. H. Huang, J. P. Dismukes, J. Shi, Q. Su, G. Wang, M. A. Razzak, and D. E. Robinson, ''Manufacturing system modeling for productivity improvement,'' *J. Manuf. Syst.*, vol. 21, no. 4, pp. 249–259, 2002.
[34] G. R. Chakravarthy, P. N. Keller, B. R. Wheeler, and S. Van Oss, ''A methodology for measuring, reporting, navigating, and analyzing overall equipment productivity (OEP),'' in *Proc. IEEE/SEMI Adv. Semiconductor Manuf. Conf. (ASMC)*, Jun. 2007, pp. 306–312.
[35] T. Dunn, *Manufacturing Flexible Packaging: Materials, Machinery, and Techniques*. Norwich, NY, USA: William Andrew, 2014.
[36] R. L. Anderson, ''Distribution of the serial correlation coefficient,'' *Ann. Math. Statist.*, vol. 13, no. 1, pp. 1–13, Mar. 1942.
[37] J. Durbin and G. S. Watson, ''Testing for serial correlation in least squares regression. III,'' *Biometrika*, vol. 58, no. 1, pp. 1–19, 1971.
[38] G. Friede, T. Busch, and A. Bassen, ''ESG and financial performance: Aggregated evidence from more than 2000 empirical studies,'' *J. Sustain. Finance Investment*, vol. 5, no. 4, pp. 210–233, Oct. 2015.

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