Extending OEE to OEE–OS: Integrating Obsolescence and Shortages into Equipment Performance Measurement

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Abstract—**Obsolescence and shortages in manufacturing enterprises are critical challenges that directly affect operational efficiency, equipment reliability, and production continuity. However, manufacturing enterprises often lack holistic operational strategies that comprehensively consider and quantify these factors while maintaining competitiveness. In particular, Key Performance Indicators (KPIs) to measure the impact of obsolescence and shortages on equipment effectiveness and to facilitate root cause analysis at the operational level are missing. Currently, the management of obsolescence and supply shortages is often addressed in a reactive or theoretical way, whereas maximizing equipment performance remains the primary focus. To transition towards a more resilient and robust manufacturing system, these factors should be systematically integrated, ensuring that operational efficiency is not compromised by aging equipment or parts shortages. To pursue this line of research in operations management, this paper introduces a conceptual approach incorporating obsolescence and shortage factors into equipment performance assessment. The approach is based on a causally-structured framework supported by a triangulation of literature review, causal modeling, and qualitative industrial feedback. It supports decision-making at both strategic and operational levels and lays the foundation for the development of a novel KPI schema, in particular focusing on the extension of OEE towards Overall Equipment Effectiveness for Obsolescence & Shortages (OEE-OS). The approach is illustrated through a PLC-based industrial case study highlighting the gap between classical OEE and OEE–OS.**

I. Introduction

Obsolescence and shortage are two closely related phenomena that manufacturers across various sectors have long faced [1]. In recent years, however, their frequency has increased due to the rapid evolution of technologies, the changing needs and requirements of customers, consumers, and users, as well as evolving expectations from public authorities and standardization bodies. In general, obsolescence refers to something becoming "outdated," whereas a shortage refers to a reduction or disruption in the availability of components, materials, or resources within the supply chain. In pioneering work conducted in the United States, which remains a key reference in the field, the commonly used term is DMSMS (Diminishing Manufacturing Sources and Materials Shortages), with shortages often arising when suppliers stop producing or selling items [2]. According to [3], obsolescence can be defined as the transition of an item or entity from a state of availability to a state of unavailability from its original manufacturer. These phenomena pose significant challenges for long-life systems. For example, an avionics control system on a commercial aircraft, once designed, developed, manufactured, and certified, may remain in service for 20 to 30 years. The functions performed by such systems are critical for safety and operational continuity, and their failure-free performance must be ensured at all times. Over such extended lifecycles, obsolescence and shortages progressively affect system maintainability, leading to increased downtime, degraded performance, and reduced operational reliability. When maintaining these systems becomes difficult due to component shortages or obsolescence, the durability and reliability of their functions are directly threatened.

Currently, many operations and maintenance management strategies rely primarily on economic indicators such as OEE, which measures performance based on availability loss, performance loss, and quality loss. While OEE is effective for evaluating operational efficiency, it primarily captures observable and short-term production losses and does not account for the impacts of obsolescence, component shortages, or the loss of critical skills and documentation. These factors correspond to structural and long-term degradation mechanisms that remain largely invisible within traditional OEE formulations. As a result, significant operational risks remain unmonitored, and the true effectiveness of systems is often overestimated.

Several OEE extensions have been proposed, including TEEP, OFE, OEEE and OSEE, to broaden performance assessment toward planned utilization, factory-level interactions, and sustainability objectives. While these approaches significantly enrich OEE interpretation, they mainly address operational or environmental dimensions and do not explicitly consider structural degradation mechanisms related to obsolescence and shortages. In parallel, research on obsolescence and DMSMS has primarily focused on lifecycle supportability and risk mitigation, with limited integration into operational performance indicators. Despite these developments, no existing work explicitly integrates obsolescence and shortages into OEE through a causal framework linking degradation mechanisms to Availability, Performance, and Quality. This gap motivates the proposed OEE–OS formulation (Overall Equipment Effectiveness Obsolescence and Shortage). The proposed approach is based on a causally grounded framework linking degradation drivers

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to operational performance, combined with a structured impact mapping and a mathematical formulation enabling their integration into OEE. The goal is to develop an operational performance indicator that captures both traditional OEE losses and the hidden impacts of obsolescence and shortages, providing a more complete picture of system performance. By integrating these factors, OEE-OS enables manufacturers and operators to make more informed decisions, allocate resources more effectively, and maintain critical system functions over long operational lifespans. More specifically, it supports the anticipation of risks related to obsolescence and shortages by explicitly linking structural degradation mechanisms to their operational consequences. Furthermore, OEE-OS provides a structured framework for monitoring and analyzing the interactions among operational risk factors, supporting proactive management of obsolescence and shortages while sustaining OEE.

The remainder of this paper is structured as follows. Section 2 reviews current practices in obsolescence and shortage management, as well as approaches to OEE assessment. Section 3 presents the conceptual modeling of OEE–OS, integrating obsolescence and shortage factors into OEE. Section 4 illustrates the approach with a case study on PLC obsolescence Finally, Section 5 concludes the paper and highlights directions for future research.

II. LITERATURE REVIEW

A. *Obsolescence and Shortage Management*

Obsolescence and shortage are closely related phenomena that increasingly affect industrial systems with long operational lifecycles. Rapid technological evolution and continuously evolving functional, regulatory, and market requirements have significantly reduced the effective lifespan of products, components, and systems, leading to frequent unavailability of originally specified items [4]. These phenomena impact not only physical components but also the long-term support and operability of systems. In the context of complex systems engineering, obsolescence management is therefore essential to ensure long-term system supportability, including reliability, availability, maintainability, and safety [5]. Obsolescence extends beyond physical degradation of hardware components. It also affects documentation, technical knowledge, and organizational capabilities. Physical elements such as mechanical, electrical, and electronic components, commonly referred to as Hardware–MaSME (Mechanical, Electrical, Electronic, and Software elements), are particularly vulnerable due to wear, technological evolution, or supplier discontinuation. However, intangible resources such as engineering know-how, operational procedures, and regulatory compliance knowledge are equally exposed to obsolescence effects [6]. Documentation obsolescence can result from outdated formats, insufficient updates, or organizational discontinuities, leading to increased maintenance errors, delays, and higher operational costs [7,8,9]. Similarly, skills obsolescence occurs when critical expertise is lost, particularly due to workforce turnover or retirement of experienced personnel, thereby compromising the sustainability of long-life systems [10].

In parallel, shortage phenomena are mainly associated with disruptions in the availability of physical components, spare parts, workforce, or tools. In the literature, these issues are commonly addressed under the concept of DMSMS (Diminishing Manufacturing Sources and Materials Shortages), which describes situations where suppliers discontinue production or support of specific items [2]. Such shortages may result in increased lead times, procurement difficulties, or forced substitution of components, all of which negatively impact system performance and maintainability.

To address obsolescence and shortage challenges, three main categories of management strategies are identified in the literature: reactive, proactive, and strategic approaches [11]. Reactive strategies address issues after they occur, while proactive and strategic approaches aim to anticipate and mitigate risks through forecasting, redesign, or life-cycle planning. The effectiveness of these strategies strongly depends on data availability, supplier collaboration, and organizational readiness. In the absence of adequate planning, obsolescence and shortages can significantly degrade maintenance efficiency, increase downtime, and threaten operational availability. Although obsolescence and shortage management are well documented in the literature, their integration into operational performance indicators remains limited. Existing works primarily focus on lifecycle risk mitigation and system supportability, without explicit linkage to performance measurement frameworks such as OEE.

B. *OEE Assessment and Extensions*

OEE is one of the most widely adopted performance indicators in industrial systems for evaluating operational efficiency. It is defined as the product of three key components : Availability, Performance, and Quality. Initially introduced by [12] within the framework of Total Productive Maintenance (TPM), OEE was designed to identify and reduce production losses caused by breakdowns, speed losses, and quality defects [13]. Since its introduction, OEE has been extensively studied and applied across various industrial contexts. [14] and more recently [15] provide a comprehensive review of OEE interpretations and limitations, highlighting its usefulness for identifying production losses while also emphasizing methodological inconsistencies in its application. [16] further analyze the integration of OEE with Lean Manufacturing, Six Sigma, and TPM, stressing the importance of data quality and consistent loss classification. Over time, several extensions of OEE have been proposed to overcome its limitations. [17] introduced Total Equipment Effectiveness Performance (TEEP), which incorporates planned downtime into performance evaluation. At a higher system level, [18] and [19] proposed Overall Factory Effectiveness (OFE), extending OEE to consider interactions between machines, processes, and information systems. More recently, environmental and sustainability dimensions have been integrated into OEE frameworks. [20] introduced Overall Environmental Equipment Effectiveness (OEEE), incorporating environmental impact indicators across the product life cycle. [21] further explored the relationship between OEE and CO_2 emissions, demonstrating the relevance of combining operational and environmental performance. Similarly, [22] proposed Overall Sustainability Effectiveness (OSEE), integrating environmental and social dimensions into production performance evaluation. Although these sustainability-oriented extensions significantly enrich the scope of OEE, they primarily address environmental and social performance objectives rather than structural system degradation mechanisms.

Despite these significant developments, existing extensions of OEE remain primarily focused on operational, environmental, or system-level efficiency. They do not explicitly consider structural degradation mechanisms such as obsolescence and shortages, which are increasingly critical in long-life industrial systems. In particular, current models fail to provide a causal representation of how these factors jointly affect Availability, Performance, and Quality. Moreover, they do not account for the component-level origins of these degradation mechanisms, nor how their effects propagate to impact system-level performance. This highlights the need for a more comprehensive performance indicator capable of integrating both observable production losses and latent structural degradation effects.

Today, no existing study has proposed a causal integration of obsolescence and shortage phenomena into OEE while explicitly linking component-level degradation drivers to system-level performance losses. This gap motivates the development of an extended indicator, OEE–OS, which captures the impact of structural degradation by establishing explicit causal relationships between component-level drivers and the OEE dimensions.

III. INTEGRATION OF OBSOLESCENCE AND SHORTAGE INTO OEE: TOWARDS OEE–OS

OEE is defined as the product of Availability, Performance, and Quality rates. This formulation provides a structured representation of operational efficiency by decomposing performance into three complementary dimensions associated with downtime, speed losses, and quality defects. OEE captures the observable effects of operational constraints but does not differentiate the nature of the mechanisms that contribute to the quality, performance and availability losses. Specifically, it does not identify those losses related to obsolescence and shortages. To better reflect the operational impact of obsolescence cases and shortages, this research work proposes an extension of OEE, namely OEE–OS.

A. Integration of degradation mechanisms

Obsolescence and shortages influence system performance by affecting maintenance operations, production conditions, and overall process availability. The proposed framework does not assume a direct impact of obsolescence and shortages on OEE. Their effects propagate through operational mechanisms such as downtime, maintenance delays, and degraded operating conditions before affecting Availability, Performance, and Quality. These phenomena originate at the component level and manifest through various mechanisms, such as component unavailability, increased repair times, degraded operating conditions, and inconsistencies in procedures or product quality. Rather than acting directly on the global OEE indicator, these mechanisms impact its three fundamental components Availability, Performance, and Quality through the propagation of component-level effects to the system level. Their influence can therefore be interpreted as a structured set of degradation drivers distributed across the OEE decomposition. The conceptual integration of these mechanisms within the OEE structure is illustrated in Fig 1.

The upper level represents degradation drivers, structured into two main categories: obsolescence and shortages. Obsolescence is decomposed into technical, documentation, and skills-related dimensions, while shortages include spare parts availability, supply lead times, supplier dependency, and workforce availability. These factors characterize the system's vulnerability. Some of them cause immediate losses while others need a longer time to manifest their effects (e.g. skills losses). Figure 1 represents causal propagation pathways linking degradation drivers to operational consequences and subsequently to OEE dimensions.

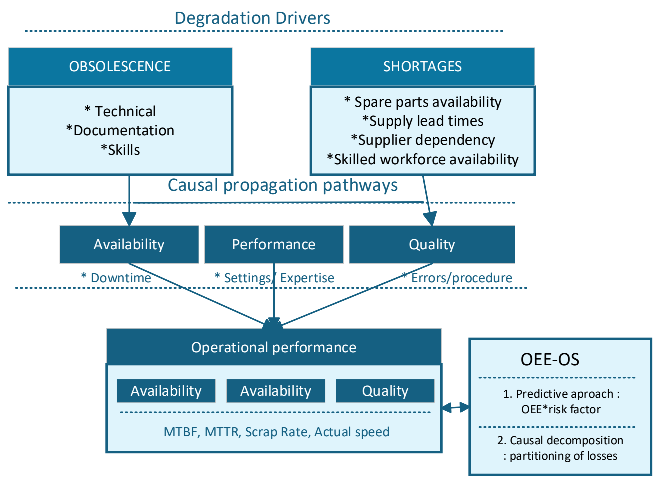

Figure 1. Integrated framework linking obsolescence and shortage drivers to OEE components through causal relationships.

The intermediate level represents causal relationships between degradation drivers and the three components of OEE. The model explicitly links each degradation mechanism to specific operational effects. Any degradation is introduced through a structured mapping of observable operational effects to their root causes as identified in Table 1. For example, component shortages primarily affect Availability through increased downtime and repair delays, whereas skills obsolescence impacts Performance through longer intervention times and suboptimal machine settings. Documentation obsolescence, in turn, affects Quality through procedural possible errors and calibration inconsistencies. This explicit causal mapping ensures that degradation effects are traceable and avoids double counting. The lower level of Figure 1 corresponds to operational state captured through the classical OEE structure, i.e. Availability, Performance, and Quality, as well as associated indicators such as MTBF, MTTR, scrap rate, and actual production speed. The causal relationships illustrated in Figure 1 are detailed in Table 1. It maps the identified types of obsolescence and shortages to their respective impacts on the three OEE components.

The table is defined based on a systematic analysis of the literature on obsolescence management, DMSMS frameworks, and maintenance engineering [23,24], combined with causal reasoning grounded in industrial practice. Beyond its qualitative role, Table 1 also constitutes the basis for parameter derivation of the model (see next sections). Each degradation mechanism is associated with a normalized severity level, which is then used to compute the contribution of obsolescence and shortages to each OEE component. This ensures traceability between qualitative assessment and quantitative formulation. In addition to this literature-based analysis, the proposed categorization and impact assessment were further informed by exploratory discussions with industrial practitioners in the automotive and railway sectors. The qualitative evaluation of impact intensity presented in Table 1 is derived from frequency of occurrence, severity of operational consequences, and the number of OEE components simultaneously affected. This representation should be interpreted as a structured modeling step supporting subsequent quantitative formalization rather than a final calibrated numerical scale.

TABLE 1 : IMPACTS OF OBSOLESCENCE AND SHORTAGES ON AVAILABILITY, PERFORMANCE, QUALITY, AND OEE-OS

Types of obsolescence/ Shortage	Nature of the impact (Obsolescence / Shortage)	Impact on Availability	Impact on Performance	Impact on Quality	Overall impact on the OEE-OS
Hardware (MaSME)	Obsolescence of mechanical/electrical components; wear and tear; sensor drift.	↑ Outages, unplanned shutdowns : Availability rate ↓	↓ Rate, ↑ micro-stops, degraded operation	↑ Variability, dimensional drift, scrap ↑	OEE-OS ↓↓↓ : sharp drop (D, P and Q impacted simultaneously)
Documentation & Know-how	Document obsolescence; loss of key skills; incorrect procedures.	Diagnostics plus longs, erreurs : Availability rate ↓	Incorrect settings, loss of rhythm	Incorrect settings → flaws, retouching ↑	OEE-OS ↓↓ : moderate to significant decrease (loss distributed over A, P, Q)
Compliance and Regulations	Regulatory obsolescence; mandatory replacement of materials or components.	Mandatory stops for compliance : Availability rate ↓	Conforming materials are less efficient : production rate ↓	Risks of non-compliance after change : scrap ↑	OEE-OS ↓↓: moderate decrease (more pronounced impact on A and P, Q affected)
Component shortage	Difficulties in procuring spare parts; suboptimal substitutions.	↑ MTTR, prolonged immobilization	Unstable pace, forced slowdowns	Alternating materials : defects ↑, unstable quality	OEE-OS ↓↓↓: very sharp decline (A and P heavily impacted, Q too)
Skills and tool shortages	Shortage of technicians, unsuitable or obsolete tools.	Slow or incomplete interventions : Availability rate ↓	Poorly maintained machines running below rated speed	Insufficient calibration : defects ↑	OEE-OS ↓↓↓: sharp decline (A, P and Q simultaneously)

B. OEE-OS: Modeling and Integration of Obsolescence and Shortage Effects

To operationalize the proposed framework, the impact of obsolescence and shortages is modelled through risk factors associated with the three dimensions of OEE: Availability, Performance, and Quality. Three factors are F_A, F_P and F_Q, representing the degradation risk affecting Availability, Performance, and Quality, respectively. These factors take values in the interval [0,1], where 0 denotes negligible impact and 1 corresponds to a critical level of degradation associated with obsolescence or supply shortage. Each factor aggregates the influence of multiple degradation mechanisms. In particular, the Availability-related factor F_A captures the effects of obsolescence, spare part shortages, and maintenance constraints. The Performance-related factor F_P reflects reductions in operational efficiency due to degraded operating conditions or insufficient expertise. The Quality-related factor F_Q accounts for process variability, documentation inconsistencies, and calibration-related deviations.

Based on the mapping provided in Table 1, the OEE–OS indicator is defined by introducing degradation effects into each OEE dimension as follows:

$$\text{OEE-OS} = (A\,(1-F_A))\,(P\,(1-F_P))\,(Q\,(1-F_Q))$$

This formulation reflects the reduction of the effective contribution of each component through the complementary term $(1-F_X)$, which represents the retained operational capability under degradation.

Since the classical OEE is defined as: OEE= A*P*Q
the above expression can be rewritten in an aggregated form:

$$\text{OEE-OS} = \text{OEE}*(1-F_{OS})$$

$$F_{OS} = 1-((1-F_A)\,(1-F_P)\,(1-F_Q))$$

This expression preserves the multiplicative structure of OEE while capturing the combined effect of degradation factors affecting Availability, Performance, and Quality. The factors F_A, F_P and F_Q quantify the level of exposure of each OEE dimension to degradation phenomena. Low values indicate limited impact, whereas high values reflect strong degradation effects. The global factor F_{OS} provides a synthetic measure of the overall degradation affecting the system. When F_{OS}=0, no degradation is present and OEE–OS is equal to the classical OEE. As F_{OS} increases, the effective performance decreases accordingly. A key property of the proposed formulation lies in its non-linear behavior. The expression of F_{OS} shows that the combined effect of multiple degradation factors is not additive. Instead, interactions between Availability, Performance, and Quality induce an amplification effect when several degradation sources are present simultaneously. The behavior of the global degradation factor as a function of the dimension-specific degradation factors is illustrated in Figure 2.

This representation highlights the non-linear aggregation of degradation effects (see also Figure.3) and shows that moderate values of F_A, F_P, and F_Q may result in a significant increase in the global degradation level. It also illustrates the interaction between the three OEE dimensions and their combined influence on system effectiveness. To further analyze the behavior of the degradation model, complementary representations are provided in Figure 3.

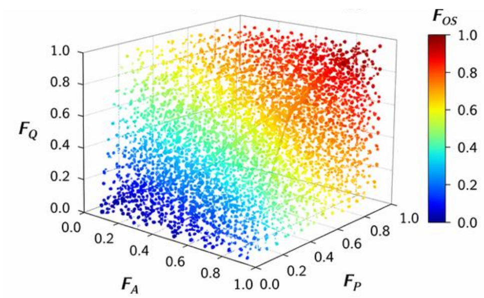

Figure 2. 3D representation of F_{OS} as a function of F_A, F_P and F_Q.

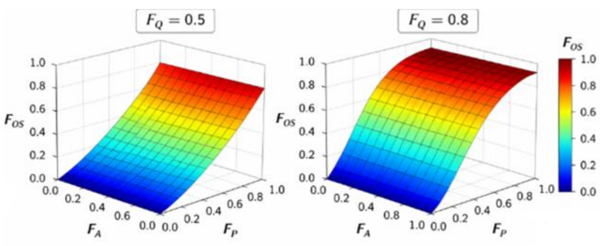

Figure 3. Planar sections of the global degradation factor F_{OS} as a function of F_A and F_P for different fixed values of F_Q

Figures 2 and 3 illustrate the mathematical behavior and sensitivity of the model. The degradation-factor values are illustrative and intended to demonstrate interaction and amplification effects rather than calibrated industrial measurements.

The evolution of the surfaces highlights the interaction effects between OEE dimensions and the amplification of degradation when multiple factors increase simultaneously. For $F_Q = 0.5$, the surface becomes progressively steeper, indicating a stronger sensitivity of the global degradation factor to variations in F_A and F_P. In the case where F_Q reaches higher levels (e.g., F_Q=0.8), even moderate increases in F_A or F_P lead to high values of F_{OS}. This behavior clearly illustrates the amplification effect inherent to the multiplicative formulation.

IV. Case Study : Programmable Logic Controllers

The Measures to Protect Populations (MPP) project implements a monitoring and alert system designed to mitigate flooding risks in a river basin. The system relies on acquisition stations equipped with Programmable Logic Controllers (PLCs), which collect real-time data from upstream tributaries. These PLCs were commissioned in 2007 and have remained in operation due to their initial industrial reliability. However, after more than fifteen years of continuous use, the system is increasingly exposed to obsolescence and shortage phenomena that affect its maintainability and operational performance.

The degradation mechanisms observed in the PLC network are consistent with the categories introduced in Table 1. Technical obsolescence primarily affects the Hardware–MaSME elements of the system. CPU modules are no longer compatible with modern communication protocols such as Ethernet/IP and Modbus TCP, while several Input/Output (I/O) cards are no longer manufactured. Power supply units also exhibit aging-related issues and must often be replaced by non-identical substitutes. Documentary obsolescence is reflected in outdated software programs, incomplete configuration files, and obsolete calibration procedures, which increase the risk of operational inconsistencies. Competence obsolescence further contributes to system degradation, as technicians originally trained on these PLCs are progressively retiring, while newer engineers have limited experience with legacy systems, leading to longer troubleshooting times and reduced maintenance efficiency. Shortage phenomena exacerbate these issues, as critical components such as I/O old cards and communication modules are difficult to procure, resulting in temporary substitutions that may degrade system performance. In parallel, the limited availability of skilled personnel affects maintenance operations and calibration activities, further reducing overall system effectiveness. Before considering degradation effects, the system exhibits high performance levels, with an Availability of 0.95, a Performance of 0.98, and a Quality of 0.99. These values lead to a baseline OEE defined as: OEE = 0.95×0.98×0.99 ≈ 0.921

Based on the structured mapping presented in Table 1, the identified degradation mechanisms are translated into dimension-level risk factors affecting Availability, Performance, and Quality. The values of F_A, F_P, and F_Q are derived from the structured mapping in Table 1 by aggregating the normalized severity of the identified degradation mechanisms, with weights assigned based on expert judgment and operational feedback. These estimates are supported by operational observations, including increased maintenance durations, extended spare-part delivery times, and the frequency of intervention delays recorded on the PLC network. In the absence of fully structured historical datasets, the values should be interpreted as representative central estimates, with an associated uncertainty reflecting variability in operational conditions. In this case study, the resulting values are estimated as:

$$F_A \approx 0.4,\ F_p \approx 0.3,\ F_Q \approx 0.2$$

The assigned values are derived from the causal mapping of Table 1 and supported by operational observations such as maintenance delays, spare-part shortages, and intervention difficulties observed on the PLC infrastructure. They represent structured central estimates rather than arbitrary coefficients. These values reflect the relative severity of the constraints affecting each OEE dimension, with Availability being the most impacted due to strong dependencies on maintenance operations and spare part availability. Substituting the estimated values yields effective performance levels of approximately 0.6 for Availability, 0.7 for Performance, and 0.8 for Quality, resulting in:

$$\text{OEE-OS} \approx 0.6 \times 0.7 \times 0.8 \approx 0.3$$

The comparison between baseline OEE and OEE–OS shows a major gap: performance drops from >0.9 to about 0.3% when obsolescence and shortages are considered.

Figure 4 highlights the impact of degradation on the three OEE dimensions. Availability is the most affected due to hardware obsolescence and component shortages, while Performance and Quality are impacted by reduced efficiency, longer intervention times, and process variability. The results show that degradation effects interact across dimensions, leading to a significant amplification of their impact.

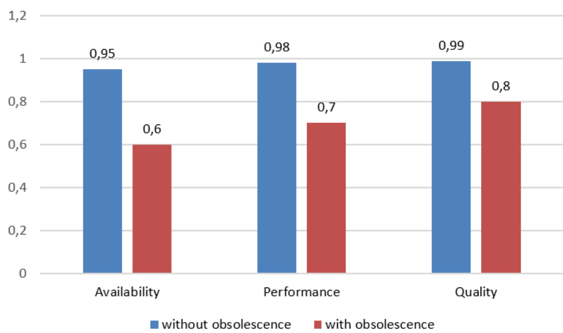

Figure 4. Comparison of the three OEE components with and without obsolescence/shortage

This case study confirms that classical OEE overestimates system performance, whereas the OEE–OS formulation provides a more realistic assessment and supports decision-making by identifying critical areas such as maintenance, spare-part management, and skill development. From a Total Quality Management perspective, OEE–OS complements traditional quality indicators by revealing hidden degradation risks affecting process stability and long-term operational capability.

V. Conclusion and Perspectives

The proposed OEE–OS indicator extends the classical OEE by explicitly integrating the effects of obsolescence and shortages, which are critical factors in long-life industrial systems. By structuring their impact through dimension-level risk factors derived from a systematic mapping of degradation mechanisms, the approach provides a more realistic and interpretable assessment of operational performance. The case study shows that a baseline OEE of 0,9 decreases to approximately 0.3 when degradation effects are taken into account, highlighting the significant gap between nominal and effective performance. This result emphasizes the importance of considering not only equipment-related losses but also constraints associated with technological aging, resource availability, and skills. Beyond performance evaluation, OEE -OS offers a consistent framework linking qualitative degradation analysis to quantitative indicators, thereby supporting maintenance planning, risk anticipation, and modernization strategies. It thus contributes to a more proactive management of aging systems and to the development of more resilient industrial infrastructures.

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