Annals on Economy, Law and Sociology, Volume 9, Number 4 Special/2026 ©2026, Academy of Romanian Scientists
Romania, October, 2026 ISSN ONLINE 2067-5704

BEYOND PPM: A MULTI-DIMENSIONAL FRAMEWORK FOR SUPPLIER QUALITY PERFORMANCE EVALUATION IN AUTOMOTIVE ELECTRONICS

Claudiu-Alexandru COVACI[1], Aurel Mihail TITU[2,3], Oana Roxana CHIVU[4] and Dan Florin NITOI[5]

[1]National University of Science and Technology POLITEHNICA Bucharest, 313 Splaiul Independenței, București, Romania, ORCID No. 0009-0003-2803-0295, covaci_claudiu99@yahoo.com
[2]Lucian Blaga University of Sibiu, 10 Victoriei Street, Sibiu, România, Corresponding author, ORCID No. 0000-0002-0054-6535, mihail.titu@ulbsibiu.ro
[3]Academy of Romanian Scientists, 3 Ilfov Street, Bucharest, Romania
[4]Quality Engineering and Industrial Technologies Department Faculty of Industrial Engineering and Robotics, Splaiul Independentei no. 313, sect 6, Bucharest, Romania, ORCID No. 0009-0009-9586-148X, oana.chivu@upb.ro
[5]Quality Engineering and Industrial Technologies Department Faculty of Industrial Engineering and Robotics, Splaiul Independentei no. 313, sect 6, Bucharest, Romania, ORCID No. 0000-0002-8929-2059, dan.nitoi@upb.ro

ABSTRACT: This paper addresses the limitations of frequency-based supplier quality evaluation in automotive electronics manufacturing by proposing and applying a multi-dimensional, risk-oriented framework. Although Parts Per Million (PPM) remains a widely used baseline indicator, defect frequency alone provides limited insight into quality-related risk in high-reliability environments. To overcome these limitations, the paper introduces a conceptual framework that complements PPM with three additional dimensions: defect severity, detection stage, and defect recurrence. Rather than relying on complex scoring or optimization models, the framework focuses on the integrated interpretation of these dimensions to construct a supplier quality risk profile that supports differentiated and proportionate decision-making. The applicability of the framework is demonstrated through an application scenario comparing two suppliers with similar PPM performance. While a PPM-only evaluation suggests comparable quality levels, the multi-dimensional assessment reveals significant differences in risk exposure driven by higher defect impact, later detection, and recurring issues for one supplier. These differences lead to distinct supplier quality actions, including escalation, audit prioritization, and targeted preventive measures. The findings indicate that extending supplier quality evaluation beyond defect frequency enhances both analytical depth and managerial relevance without increasing methodological complexity. The proposed framework offers a practical decision-support approach suited to complex and safety-critical manufacturing contexts.
KEYWORDS: Supplier quality; PPM; Risk evaluation; Automotive; Multi-dimensional framework.

DOI 10.56082/annalsarscieco.2026.4.68

1. INTRODUCTION

The automotive industry is undergoing significant transformations driven by technological advancements, sustainability requirements, and increasing product complexity. In this context, supplier quality performance plays a critical role in ensuring operational stability and product reliability, particularly in automotive electronics, where even low-frequency defects may lead to substantial functional or safety risks.

Supplier quality performance has traditionally been assessed using quantitative metrics such as Parts Per Million (PPM), which measure the frequency of nonconforming parts. Although widely adopted, PPM provides a limited view of supplier performance, as it does not reflect defect severity, detection stage, recurrence behaviour, or the effectiveness of supplier response. Consequently, suppliers with similar PPM values may exhibit markedly different quality risk profiles.

Prior research indicates that supplier quality performance is inherently multi-dimensional and influenced by a combination of technical and organizational factors. Krause (2006) highlight the role of supplier development, buyer commitment, and social capital in improving performance outcomes across quality, cost, flexibility, and delivery dimensions, suggesting that single-dimensional performance metrics are insufficient to capture supplier behaviour comprehensively. Similarly, Kim (2012) demonstrate that effective quality management practices and structured use of quality-related data enhance collaboration and continuous improvement, extending the scope of supplier performance evaluation beyond defect rates alone.

Supplier integration in New Product Development (NPD) has also been shown to positively influence quality outcomes. Petersen (2004) argue that early supplier involvement contributes to improved product quality and reduced development costs, reinforcing the need for performance evaluation approaches that account for broader supplier contributions. Furthermore, meta-analytic evidence by Nair (2005) confirms strong relationships between leadership, supplier quality management practices, and overall performance, supporting a holistic perspective on supplier evaluation.

Despite these insights, supplier performance assessment in the automotive industry, particularly in serial production, continues to rely predominantly on PPM-based scorecards. This creates a gap between the complexity of supplier quality behaviour discussed in the literature and the simplicity of metrics applied in practice, a gap that is especially critical in automotive electronics.

To address this limitation, this paper proposes a multi-dimensional supplier quality performance evaluation framework that extends the traditional PPM-based approach.

Rather than replacing PPM, the framework operationalizes established quality management concepts, such as defect severity, detection effectiveness, recurrence behaviour, and supplier responsiveness, into complementary performance dimensions, enabling a more comprehensive and risk-oriented assessment of supplier quality performance.

2. LIMITATIONS OF PPM-BASED SUPPLIER PERFORMANCE EVALUATION

Parts Per Million (PPM) is widely used in the automotive electronics industry as a primary indicator of supplier quality performance due to its simplicity and ease of comparison. By quantifying the frequency of nonconforming parts, PPM provides a basic measure of delivered quality. However, when used as a standalone metric, PPM offers a limited and potentially misleading view of supplier quality performance.

Limited representation of supplier quality performance

PPM captures only defect frequency and fails to reflect the multi-dimensional nature of supplier quality performance. In practice, supplier performance is influenced by a broader set of factors, including responsiveness, service quality, and the effectiveness of supplier support activities (Ohdar & Ray, 2004). As emphasized by Choi and Hartley (1996), long term buyer-supplier relationships and sustained performance improvements require evaluation approaches that extend beyond single quantitative indicators.

In particular, PPM does not provide visibility into the:

- severity or criticality of detected defects
- stage at which defects are detected within the quality chain
- recurrence of similar defects over time
- effectiveness of supplier reaction and corrective actions.

As a result, suppliers with identical PPM values may present significantly different quality risk profiles.

Lack of severity and risk differentiation

Another fundamental limitation of PPM is its inability to differentiate between defects with vastly different impacts.

Minor cosmetic deviations and functionally critical defects are treated equally within PPM calculations, despite their unequal consequences for product reliability and operational risk.

This limitation is particularly critical in automotive electronics, where low defect frequencies may still be associated with high functional or safety risks.

Consequently, PPM-based evaluations may mask suppliers that exhibit:

- low defect frequency but high defect severity
- infrequent but systemic quality issues
- acceptable PPM results combined with unstable processes.

Predominantly reactive and lagging nature

PPM is inherently a lagging indicator, reflecting quality outcomes only after defects have occurred. Its use therefore promotes a reactive approach to supplier quality management, where actions are triggered post-factum rather than guided by early warning signals. Nair (2005) notes that an excessive focus on outcome-based metrics may discourage deeper process improvement, as suppliers concentrate on meeting minimum defect thresholds instead of addressing root causes and process stability.

Furthermore, PPM does not capture:

- whether corrective actions are effective
- whether similar defects reappear after closure
- whether process stability is improving or deteriorating.

Risk of misleading performance interpretation

Exclusive reliance on PPM may lead to misleading interpretations of supplier performance trends. Suppliers may maintain acceptable PPM levels while simultaneously exhibiting recurring issues, delayed detection, or inadequate response to deviations.

Such patterns often remain invisible in PPM-based scorecards, potentially delaying escalation, audits, or targeted supplier development activities (Kuo, 2010).

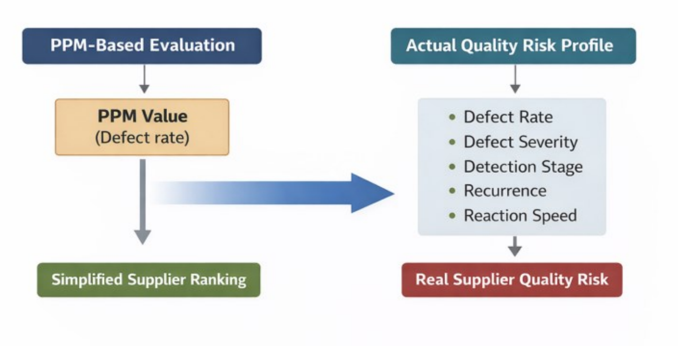

Figure 1. Limitations of PPM-based supplier evaluation

In summary, while PPM remains a useful indicator for monitoring defect frequency, it is insufficient as a standalone measure of supplier quality performance in complex automotive electronics environments. These limitations underline the need for a multi-dimensional evaluation approach that complements PPM with additional performance dimensions addressing defect severity, detection effectiveness, and recurrence behavior. This need provides the foundation for the framework proposed in the following section.

Quality performance aspect	Captured by PPM	Not captured by PPM
Defect frequency	✓	–
Defect severity (impact)	–	✓
Detection stage	–	✓
Defect recurrence over time	–	✓
Overall quality risk profile	–	✓

Table 1. PPM coverage vs. quality risk dimensions

3. DEVELOPMENT OF THE MULTI-DIMENSIONAL SUPPLIER QUALITY PERFORMANCE FRAMEWORK

The limitations of PPM-based supplier performance evaluation discussed in the previous section highlight the need for a broader and more informative approach to assessing supplier quality, particularly in the context of automotive electronics. While PPM remains a useful indicator for monitoring defect frequency, it does not adequately reflect quality-related risk, nor does it support differentiated decision-making when suppliers exhibit similar defect rates but different quality behaviours.

To address these limitations, this study proposes a multi-dimensional supplier quality performance framework designed to complement traditional PPM-based evaluation. The framework shifts the focus from single-metric assessment toward a structured quality risk profile that integrates multiple, non-redundant performance dimensions. Rather than representing an operational process, the framework provides a conceptual evaluation logic that supports risk-oriented supplier assessment and managerial decision-making.

3.1 Conceptual Foundation of the Framework

Supplier quality risk cannot be fully described through defect frequency alone. In complex manufacturing environments, suppliers with identical PPM values may exhibit fundamentally different risk profiles, driven by differences in defect severity, detection stage, and recurrence behaviour.

The proposed framework addresses this gap by extending traditional PPM-based evaluation with complementary quality performance dimensions, enabling a structured and risk-oriented assessment of supplier quality performance.

3.2 Framework Dimensions and Evaluation Logic

The proposed multi-dimensional framework evaluates supplier quality performance through a limited set of complementary dimensions, each addressing a specific limitation of traditional PPM-based assessment. Rather than expanding supplier evaluation toward broad managerial or commercial criteria, the framework focuses explicitly on quality-related risk, which is particularly critical in automotive electronics characterized by high functional integration and low tolerance for failure.

Frequency-based dimension: Parts Per Million (PPM)

PPM remains the baseline indicator within the framework, representing the frequency of detected nonconforming parts. Its widespread adoption and simplicity make it a useful starting point for supplier quality evaluation. However, as discussed in Section 2, PPM alone provides limited insight into the nature and impact of quality issues. Within the proposed framework, PPM is therefore retained as a contextual indicator, rather than a standalone measure of supplier performance.

Impact-based dimension: Defect Severity

To address the lack of impact differentiation in PPM-based evaluation, defect severity is introduced as a separate dimension. Defect severity reflects the functional and operational consequences of nonconformities, distinguishing between minor deviations and defects with critical implications. Severity-based thinking is well established in quality management, particularly through risk analysis tools such as Failure Mode and Effects Analysis, where severity is used to assess potential impact rather than occurrence alone (Flynn, 1995). Incorporating severity as an explicit evaluation dimension enables a more realistic assessment of supplier-related quality risk, especially in cases where low defect frequency coincides with high potential impact.

Visibility-based dimension: Detection Effectiveness

Another limitation of PPM is its inability to indicate where defects are detected along the quality chain. Detection effectiveness captures the stage at which nonconformities are identified, differentiating between early detection at incoming inspection and late detection during downstream processes. Prior research has shown that late detection significantly amplifies quality-related costs and operational risk (Shin, 2000). By incorporating detection effectiveness, the framework adds a visibility-oriented perspective that highlights weaknesses in supplier process control and quality assurance maturity.

Stability-based dimension: Defect Recurrence

The stability-based dimension evaluates whether detected defects represent isolated events or recurring issues over time. Defect recurrence is a strong indicator of systemic weaknesses and ineffective corrective actions, yet it is not reflected in PPM values. Recurrent quality issues often persist despite acceptable defect rates, masking underlying process instability (Nair, 2005). Including recurrence behavior as a distinct dimension enables differentiation between suppliers that effectively eliminate root causes and those that repeatedly address symptoms.

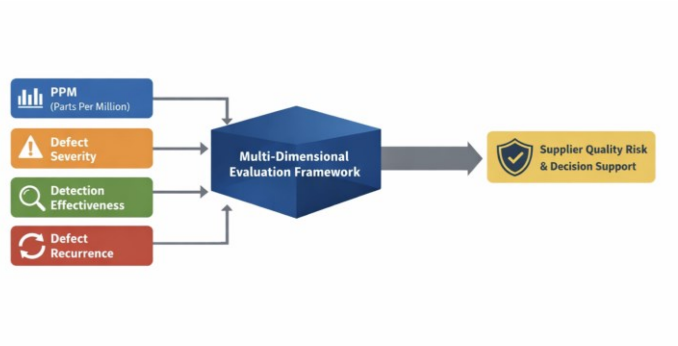

Figure 2. Multi-dimensional supplier quality performance framework

Integrated evaluation logic

The evaluation logic of the framework does not rely on mathematical aggregation, weighting schemes, or multi-criteria optimization algorithms. Instead, the individual dimensions are interpreted jointly to form a qualitative supplier quality risk profile. This integrated perspective enables differentiation between suppliers with similar PPM values but fundamentally different quality behaviours, supporting more informed decisions regarding escalation, audit focus, and preventive actions.

4. APPLICATION OF THE MULTI-DIMENSIONAL FRAMEWORK IN AUTOMOTIVE ELECTRONICS

This section demonstrates how the proposed framework can be applied in a typical automotive electronics context to support supplier quality decisions. The intent is not to provide a full statistical validation, but to show how a multi-dimensional, risk-oriented evaluation can translate into clearer differentiation and more targeted actions than a frequency-only assessment. Risk-based quality approaches aligned with modern quality management principles have been reported as effective in practice, particularly when organizations shift attention from defect counting to risk identification and mitigation (Prata, 2020).

4.1 Context of the application scenario

The application scenario reflects serial production supply of an automotive electronics component with incoming inspection and downstream functional verification. Two suppliers (we will call them Supplier A and Supplier B) deliver comparable part families under similar logistics conditions. Both are initially classified as acceptable based on routine quantitative monitoring, and both are subject to the same standard escalation thresholds.

4.2 PPM-based supplier evaluation

Under a PPM-only approach, Supplier A and Supplier B appear similarly performing: defect frequency is comparable and remains within the accepted threshold. Based on this view, both suppliers would typically receive the same priority level in supplier management (e.g.: routine monitoring and standard complaint handling), with no strong trigger for differentiated audit focus or intensified preventive action.

4.3 Multi-dimensional evaluation results

Applying the proposed framework, the same two suppliers are evaluated across the complementary dimensions introduced in Section 3.2: impact (severity), visibility (detection effectiveness), and stability (recurrence), while retaining PPM as the baseline frequency indicator.

Severity (impact): Nonconformities associated with Supplier A are primarily minor and limited in functional impact. In contrast, the most recent nonconformities associated with Supplier B are linked to higher functional relevance (e.g.: failure modes affecting fit/function or downstream test performance). This creates a materially different risk profile despite comparable defect frequency.

Detection effectiveness (visibility): For Supplier A, deviations are predominantly identified at incoming inspection. For Supplier B, deviations are more frequently detected downstream (e.g.: during in-process checks or functional test), indicating weaker upstream control or less effective defect containment. Prior research indicates that operational practices and monitoring intensity influence detection capability, supporting the practical relevance of detection-stage information when prioritizing supplier actions (Zhu & Sarkis, 2004).

Recurrence (stability): Supplier A shows low recurrence of similar defect modes after corrective action closure. Supplier B shows repeated reappearance of similar defect families over time, suggesting insufficient root-cause elimination or unstable process control. In practical risk-oriented quality systems, recurring issues are treated as stronger signals for escalation and preventive intervention than isolated events (Prata, 2020).

Collectively, these dimensions produce a clear divergence: Supplier A remains a low-risk supplier under the framework, while Supplier B presents elevated quality risk driven by higher impact, reduced visibility, and recurrence behaviour. Multi-dimensional supplier assessment frameworks have been discussed in the literature as a means to expand the decision basis beyond single metrics and to better align supplier management actions with observed performance patterns (Zhang, 2023).

Table 2 shows that while a PPM-only evaluation leads to identical conclusions for both suppliers, the multi-dimensional framework reveals substantial differences in quality risk profiles driven by severity, detection stage, and recurrence behaviour.

Evaluation perspective	Dimension	Supplier A	Supplier B	Interpretation
PPM-based evaluation	Average PPM	~140	~145	Comparable defect frequency
	PPM trend	Stable	Stable	No significant deviation
	PPM-based conclusion	**Acceptable**	**Acceptable**	No differentiation
Multi-dimensional evaluation	Frequency (PPM)	~140	~145	Similar baseline performance
	Impact (defect severity)	Low	High	Supplier B exposes higher functional risk
	Visibility (detection stage)	Incoming inspection	Downstream testing	Late detection increases risk
	Stability (defect recurrence)	No recurrence	Recurrent issues	Indicates systemic weakness
	Overall quality risk	**Low**	**High**	Different quality decisions required

Table 2. Comparison of supplier evaluation outcomes using PPM-only and multi-dimensional framework

4.4 Impact on supplier quality decisions

The practical value of the framework is that it supports differentiated, risk-oriented decisions without requiring complex scoring algorithms. In the scenario above, the framework would justify distinct actions:

- Supplier A (lower risk profile): maintain routine monitoring; preserve standard sampling and periodic review; focus on sustaining control plans.
- Supplier B (higher risk profile): escalate to intensified containment expectations; prioritize targeted process audit scope toward suspected failure mechanisms; increase verification intensity until stability is demonstrated; require corrective action evidence specifically addressing recurrence and detection weaknesses.

Such differentiation aligns with the intent of risk-based quality management: allocating escalation, audit capacity, and preventive actions in proportion to risk rather than frequency alone (Prata, 2020). The framework therefore functions as a practical decision-support layer that helps translate quality signals into proportional supplier management responses.

5. DISCUSSION AND MANAGERIAL IMPLICATIONS

The results presented in the previous sections highlight the practical relevance of moving beyond frequency-based supplier quality evaluation toward a risk-oriented, multi-dimensional perspective. While PPM remains a useful baseline indicator, the application example demonstrates that defect frequency alone is insufficient for supporting differentiated supplier quality decisions in complex automotive electronics environments.

From a quality management perspective, the proposed framework contributes by structuring supplier evaluation around how often defects occur, how severe they are, where they are detected, and whether they recur over time. This combination enables organizations to distinguish between suppliers that appear similar under PPM-based monitoring but exhibit fundamentally different quality behaviours and risk exposures. Such differentiation is particularly important in high-reliability contexts, where low-frequency but high-impact defects can lead to disproportionate operational and reputational consequences.

From a managerial standpoint, the framework supports proportionate and targeted decision-making. Rather than applying uniform escalation rules based solely on defect thresholds, quality managers can prioritize audits, containment actions, and supplier development activities according to the observed quality risk profile. This approach aligns with contemporary risk-based quality management principles, which emphasize allocating resources and controls based on risk exposure rather than metric compliance alone (Prata, 2020).

In the automotive electronics context, where supplier portfolios often include a mix of mature and developing suppliers, the framework also supports more effective supplier communication. By explicitly separating frequency, impact, visibility, and stability dimensions, quality discussions can move away from disputes over PPM values toward a shared understanding of risk drivers and improvement priorities. This can facilitate more constructive supplier engagement and more focused corrective action planning.

Despite its advantages, the proposed framework has certain limitations. First, it is conceptual and intentionally avoids formal scoring or weighting mechanisms, which may limit direct comparability across large supplier bases without additional internal guidelines. Second, the application presented reflects a generic scenario; while representative, it does not substitute for empirical validation across multiple products or production phases. Future research could therefore explore quantitative extensions of the framework or assess its effectiveness across different supplier maturity levels and industrial contexts.

6. CONCLUSIONS

This paper addressed the limitations of frequency-based supplier quality evaluation by proposing and applying a multi-dimensional framework tailored to the needs of automotive electronics manufacturing. While Parts Per Million (PPM) remains a widely used and useful baseline indicator, the analysis demonstrates that defect frequency alone is insufficient for capturing quality-related risk in complex, high-reliability supply chains.

The proposed framework extends traditional evaluation by integrating complementary dimensions related to defect impact, detection effectiveness, and recurrence behaviour. Through a structured application scenario, the framework showed its ability to differentiate between suppliers with similar PPM values but fundamentally different quality risk profiles, thereby supporting more informed and proportionate supplier quality decisions.

From a practical perspective, the framework offers a decision-support approach that is compatible with existing quality management practices and does not rely on complex scoring or optimization methods. Its focus on risk-oriented interpretation enables quality managers to better prioritize escalation, audit focus, and preventive actions based on observed quality behaviour rather than metric compliance alone.

In conclusion, adopting a multi-dimensional perspective on supplier quality performance enhances both the analytical depth and managerial relevance of supplier evaluation in automotive electronics. Future work may further explore quantitative extensions of the framework or validate its applicability across broader supplier portfolios and industrial contexts.

7. REFERENCES

[1] Choi, T. Y. and Hartley, J. L. (1996). An exploration of supplier selection practices across the supply chain. Journal of Operations Management, 14(4), 333–343. https://doi.org/10.1016/s0272-6963(96)00091-5

[2] Flynn, B. B., Schroeder, R. G., & Sakakibara, S. (1995). The impact of quality management practices on performance and competitive advantage. Decision Sciences, 26(5), 659–691. https://doi.org/10.1111/j.1540-5915.1995.tb01445.x

[3] Kim, D., Kumar, V., & Kumar, U. (2012). Relationship between quality management practices and innovation. Journal of Operations Management, 30(4), 295–315. https://doi.org/10.1016/j.jom.2012.02.003

[4] Krause, D. R., Handfield, R., & Tyler, B. B. (2006). The relationships between supplier development, commitment, social capital accumulation and performance improvement. Journal of Operations Management, 25(2), 528–545. https://doi.org/10.1016/j.jom.2006.05.007

[5] Kuo, R., Wang, Y., & Tien, F. (2010). Integration of artificial neural network and MADA methods for green supplier selection. Journal of Cleaner Production, 18(12), 1161–1170. https://doi.org/10.1016/j.jclepro.2010.03.020

[6] Nair, A. (2005). Meta-analysis of the relationship between quality management practices and firm performance—implications for quality management theory development. Journal of Operations Management, 24(6), 948–975. https://doi.org/10.1016/j.jom.2005.11.005
[7] Ohdar, R. and Ray, P. K. (2004). Performance measurement and evaluation of suppliers in supply chain: an evolutionary fuzzy-based approach. Journal of Manufacturing Technology Management, 15(8), 723–734. https://doi.org/10.1108/17410380410565311
[8] Petersen, K., Handfield, R., & Ragatz, G. (2004). Supplier integration into new product development: coordinating product, process and supply chain design. Journal of Operations Management, 23(3–4), 371–388. https://doi.org/10.1016/j.jom.2004.07.009
[9] Prata, E. R. B. d. A., Chaves, J. B. P., Gomes, S. G. S., & Passos, F. J. V. (2020). Statistical quality control in the food industry: a risk-based approach. International Journal of Quality & Reliability Management, 38(2), 437–452. https://doi.org/10.1108/ijqrm-08-2019-0272
[10] Shin, H., Collier, D., & Wilson, D. D. (2000). Supply management orientation and supplier/buyer performance. Journal of Operations Management, 18(3), 317–333. https://doi.org/10.1016/s0272-6963(99)00031-5
[11] Zhang, Z., Zhang, N., Sun, J., & Wang, J. (2023). Emerging trends and developments in green supplier management: A bibliometric review and analysis. Journal of Intelligent & Fuzzy Systems, 45(3), 3929–3949. https://doi.org/10.3233/jifs-222019
[12] Zhu, Q. and Sarkis, J. (2004). Relationships between operational practices and performance among early adopters of green supply chain management practices in Chinese manufacturing enterprises. Journal of Operations Management, 22(3), 265–289. https://doi.org/10.1016/j.jom.2004.01.005