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Research on Cost-Effective Optimization Strategies for Controlling Safety-Critical Parts

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Abstract: This research aims to demonstrate that, while adhering to the baseline of safety regulations, effective cost-optimized control of safety-critical parts can be achieved through strategies such as precise classification, process method optimization, supply chain collaboration, and data-driven approaches.

Keywords: Safety-critical parts control; Critical characteristics; Cost optimization

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1. Introduction

Under the constraints of economic efficiency and cost considerations within enterprises, optimizing the control of safety-critical parts is a highly practical and crucial issue. Within strict quality management system frameworks like IATF 16949, arbitrarily lowering the control level for genuine safety-critical parts is generally not permitted, especially when failure consequences involve personal safety, major regulatory violations, or catastrophic environmental impacts [1–4].

The reason lies in the non-negotiability of "unacceptable risk": The core definition of safety-critical parts stems from the severity of their failure consequences. Even if a failure could be 100% detected or easily repaired, the occurrence of the failure event itself (e.g., brake failure causing an accident, even if repairable afterwards) results in irreversible losses (casualties, massive fines, brand destruction). The core objective of safety-critical parts control is to prevent failures from occurring, not to rely on post-failure detection and repair.

Regulatory mandates concerning safety and environmental protection, customer requirements for safety-critical parts, and the core spirit of IATF 16949–prevention and continual improvement, not tolerating risk and dealing with it afterwards–all impose high demands on controlling safety-critical parts. However, this does not preclude seeking more cost-effective control methods.

2. Precise identification and classification

The purpose of precise identification and classification is to ensure resources are allocated where they matter most. This can be approached from two aspects: Strict application of risk analysis tools like FMEA to distinguish critical from important characteristics and adopt different control strategies.

2.1. Strict application of risk analysis

Focus on severity: Only items with extremely high severity should be classified as "safety-critical parts/characteristics." Avoid over-escalating the level of "important but not critical" items.

Utilize occurrence and detection for control strategy adjustment, while the classification of a safety-critical part cannot be lowered, Occurrence (O) and Detection (D) ratings can influence the intensity and cost of specific control measures [5]. For failure modes with low occurrence, monitoring frequency might be reduced (while still ensuring basic prevention and detection capability) or lower-cost preventive measures employed. For failure modes with high detection, if existing detection methods (e.g., automatic testing, 100% inline inspection) are highly reliable and cost-controlled, additional expensive preventive measures may be unnecessary (**Figure 1**). However, reliance solely on detection is insufficient; prevention is still a core method.

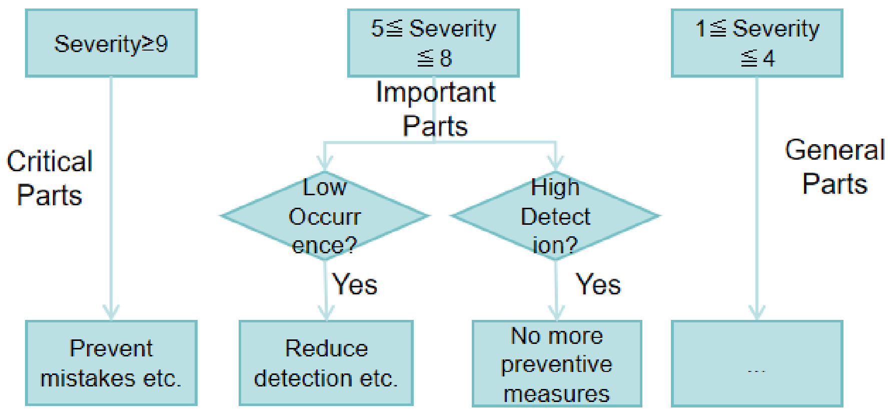

Figure 1. Critical characteristic SOD (Severity-Occurrence-Detection) decision tree

2.2. Distinguishing critical from important

For critical Parts/Characteristics for which failure consequences are highly severe (S9–10), involving safety, regulations, or loss of core functionality, strict control is mandatory, but methods can be optimized (see Section 3) [6].

For important Parts/Characteristics for which failure consequences are moderately severe (S5–8), primarily affecting function, performance, customer satisfaction, or incurring high repair costs, relatively economical control strategies can be implemented (e.g., sampling inspection, process monitoring). And "detectable/easily repairable failure" can be a reasonable factor for lowering the control level (from Important to General).

3. Optimizing control methods themselves

Optimizing control methods does not mean reducing control rigor or relying solely on post-failure detection and repair. Instead, it involves shifting controls upstream, emphasizing mistake-proofing (poka-yoke) over detection, aiming for higher efficiency and lower cost, including the following aspects.

3.1. Mistake-proofing (poka-yoke) over detection

Mistake-proofing may require a higher upfront investment but yields the lowest long-term cost. One successful poka-yoke implementation can eliminate significant subsequent detection costs, rework/scrap costs, and field failure costs. Design simple, reliable mistake-proofing devices, prioritize mechanical, low-cost, easy-to-maintain solutions over complex automated inspection. Utilize existing resources, integrate poka-yoke functions into existing equipment or processes. For example, using sensors on a PLC to detect liquid flow position and trigger alarms via logic if values exceed setpoints.

3.2. Enhancing SPC effectiveness and efficiency

Optimize control chart selection, for continuous data, Xbar-R charts are often more sensitive and efficient than attribute charts like P charts (**Figure 2**: Xbar-R charts provide richer, more sensitive continuous data information). Rationalize sample frequency and size, based on process capability and risk analysis (Occurrence), and scientifically calculate the minimum required sample size and frequency to avoid oversampling. Adopt automated data collection and charting, use MES systems or simple sensors for automatic data capture, real-time SPC charting, and automatic alarms to reduce labor costs [7–8].

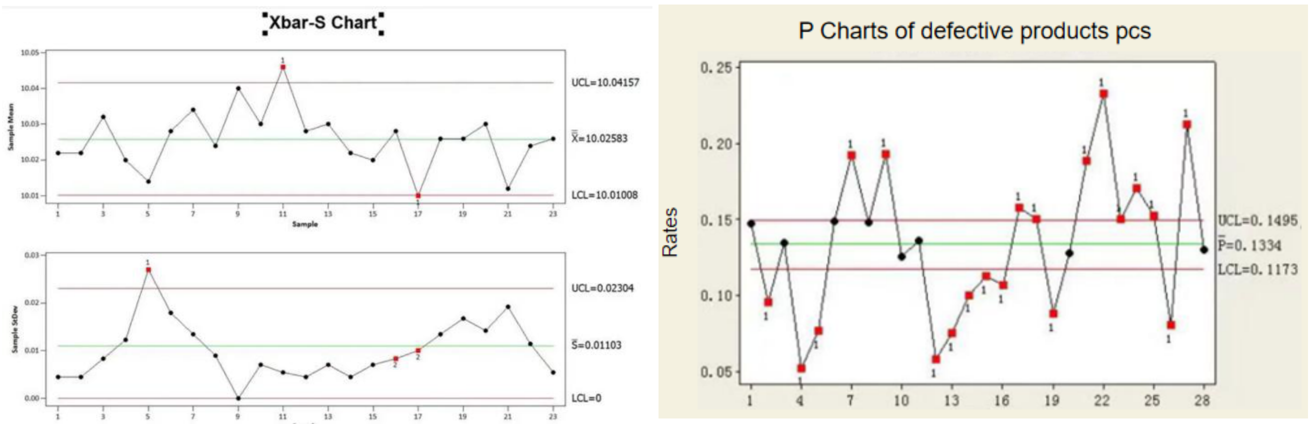

Figure 2. Comparison between Xbar-R charts and P charts

3.3. Modular testing and layered strategy

Modular testing: Testing critical characteristics at the sub-assembly or module level is more economical and facilitates easier problem localization than testing only at the final product stage. Use a layered sampling/testing strategy, combine supplier incoming inspection, in-process inspection, and final inspection, implementing sampling or testing schemes of varying strictness at different stages (**Figure 3**: Modular testing and layered strategy), to avoid relying solely on expensive 100% testing at the final stage.

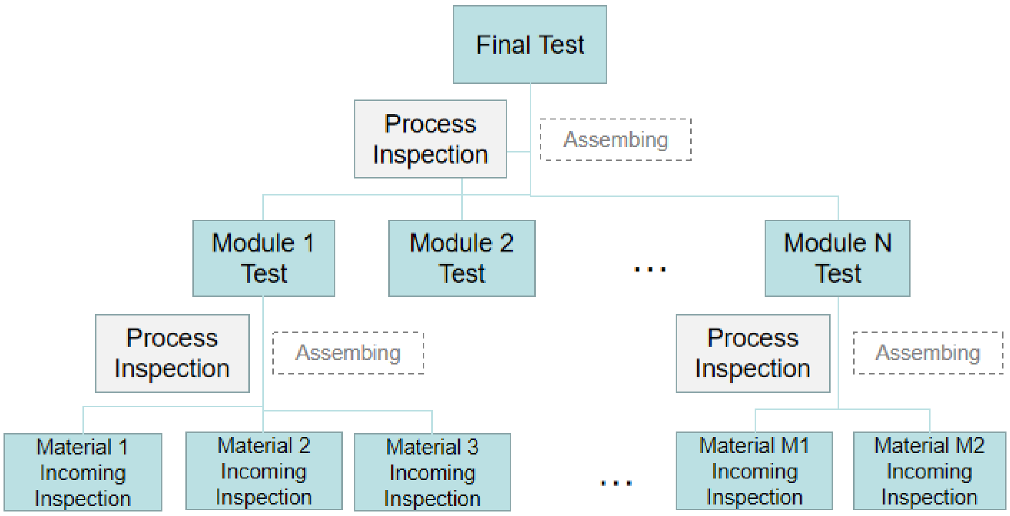

Figure 3. Modular testing and layered strategy

3.4. Measurement system optimization

Select reliable, low-maintenance-cost gauges and instruments that meet precision requirements (MSA). Employ multi-parameter gauges or automated measurement equipment to improve measurement efficiency. While initial investment is higher, long-term gains from depreciation, labor savings, and reduced misjudgments improve overall efficiency. Conduct regular maintenance and calibration to ensure measurement system stability and reliability, to prevent misjudgments and extra costs due to measurement errors.

3.5. Standardization and training

Develop clear work instructions to reduce operational and inspection errors, lowering failures and rework caused by human error. Implement effective training to ensure operators and inspectors truly understand the importance of safety-critical parts and the correct operation/inspection methods, to improve first-pass yield.

4. Design optimization and supply chain collaboration

Design optimization and supplier collaboration are critical links, serving as the source for identifying and controlling critical characteristics and parts.

4.1. Design optimization

Simplify design: Such as reducing part count and complexity, to lower the associated number of critical characteristics. Enhance design robustness: Design products to be insensitive to minor manufacturing variations (high Cp/Cpk), to reduce the demand for stringent process control. Design for testability (DfT): Incorporate features in the design that facilitate economical and effective testing (e.g., reserved test points).

4.2. Early supplier involvement

Engage key suppliers during the design phase to co-design parts and participate in manufacturing processes. This helps to reduce the difficulty and cost of achieving critical characteristics from the source.

4.3. Supplier capability building

Invest in helping suppliers to improve their process capability and quality management level, especially regarding safety-critical parts control. Associating FMEAs, providing training, process audit coaching, and sharing best practices are all useful methods. These could ensure stable incoming quality, reduce internal inspection costs, and reduce failure risks.

5. Leveraging data and continuous improvement

Collect effective real data and utilize it for analysis to drive improvement [9–10].

5.1. Cost-benefit analysis

Conduct quantitative analysis of the costs (investment) versus benefits (reduced failure costs, rework, warranty, recall risk) for proposed control measures (**Table 1**). Prioritize measures with a high return on investment (ROI).

Table 1. Example of ROI template

Styles	January	February	March	April	May	June
Cost						
Equipment cost						
Expenses of labour						
Training cost						
…						
Benefit						
Reduced failure costs						
Reduced rework costs						
Reduced maintenance costs						
…						
Profit						

5.2. Monitoring and feedback loop

Monitor the effectiveness of implemented safety-critical part controls (e.g., process capability indices, defect rates, poka-yoke effectiveness, failure costs) and actual costs (e.g., per-unit control cost, failure cost reduction rate) closely. Use data to drive decisions and continuously optimize control strategies (e.g., adjusting SPC parameters, improving poka-yoke devices, optimizing inspection points).

5.3. Lessons learned database

Establish and utilize a repository of historical failure data and improvement experiences to guide risk identification and control strategy formulation in new projects, to avoid redundant investments.

6. Conclusion

For genuine safety-critical parts and characteristics, without lowering core requirements (safety, regulations), significant optimization is achievable. By implementing core strategies–precise classification, prioritizing mistake-proofing, efficient SPC/measurement, design optimization, supply chain collaboration, and data-driven decision making–the focus on "total cost" is elevated. This approach reduces the total cost of quality (prevention + appraisal + failure) while simultaneously enhancing system efficiency, freeing resources for higher-value activities, strengthening supply chain resilience, and boosting enterprise competitiveness.

Disclosure statement

The author declares no conflict of interest.

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