Engineering for Cosmetic Product Quality and Supply Continuity: Modeling Defect Escape, Batch Release Latency, and Complaint Risk Under Measurement Uncertainty

Sreymao Pech[1*], Ayesha Rahman[2]

Author Affiliation:
[1]Faculty of Sciences, University of Battambang, Battambang 02000, Cambodia
[2]Department of Computer Science, Asia Pacific University of Technology & Innovation (APU), Kuala Lumpur 57000, Malaysia

***Corresponding Author**
Faculty of Sciences, University of Battambang, Battambang 02000, Cambodia
Email: sreymao.pech@ubb.edu.kh

ABSTRACT

This article presents an engineering-oriented framework that treats cosmetic quality assurance as an end-to-end decision system and quantifies how uncertainty propagates from incoming raw material variability through in-process controls, laboratory testing, and release decisions into distributional outcomes relevant to production and brand risk, including probability of defect escape, probability of false rejection, time-to-release distributions, complaint incidence risk, and expected cost per batch. A scenario-based quantitative study is developed for representative skin-care and color cosmetic products across three risk profiles, comparing four operational architectures: baseline end-of-line testing, increased testing density without governance, model-based risk scoring with limited drift handling, and a governance-optimized two-tier approach that constrains nuisance rejections while improving early detection through drift-aware controls, stratified sampling, and staged release decisions. Results indicate that defect escape is dominated by sampling and release latency tails rather than by mean lab accuracy, that expanding tests without governance can increase false rejection and slow release, and that a two-tier governed strategy reduces defect escape while stabilizing throughput and complaint risk. Up to three copy-ready tables and full prompts for data-driven figures are provided for Techne submission.

Keywords: Cosmetics Quality Control, Batch Release, Defect Escape, Microbial Risk, Viscosity Drift.

1. INTRODUCTION

The beauty industry is often viewed through the lens of branding, trend cycles, and consumer behavior, yet the operational foundation of a successful beauty business is reliability in product quality and supply continuity, because consumer trust in cosmetics is fragile and defects that might be tolerated in other consumer goods can quickly generate complaint cascades, retailer penalties, and regulatory exposure (Kırılmaz & Erol, 2017; Mohaghar et al., 2021). Unlike many industrial sectors where failure is defined by mechanical breakdown, cosmetic product failure is typically a probabilistic defect escape event: a batch that appears acceptable under limited sampling and measurement uncertainty is released, distributed, and then exhibits instability, contamination, or performance inconsistency in the field (Fazli et al., 2015; Katsaliaki et al., 2022). These events

can be infrequent but high-consequence, particularly for products that are applied to skin and near sensitive areas, and they become more likely as product portfolios expand, ingredient supply chains diversify, and production is accelerated to meet market demand.

Cosmetic manufacturing reliability is increasingly challenged by formulation complexity and ingredient variability. Modern products may incorporate active ingredients, natural extracts with batch-to-batch composition variability, emulsifiers sensitive to shear history, pigments and pearls whose dispersion affects color and texture, and packaging systems that interact chemically or mechanically with formulation (Azadegan & Jayaram, 2017; Manouchehri et al., 2020). Each of these factors introduces variability that must be controlled through process parameters such as mixing time, temperature profiles, vacuum deaeration, and fill conditions, and the product must then be verified through laboratory measurements such as viscosity, pH, density, microbial challenge indicators, and sensory proxies like odor and colorimetric coordinates. However, many of these measurements have nontrivial uncertainty and can be influenced by sampling location within tanks, measurement instrument drift, operator technique, and environmental conditions, meaning that "meeting specification" is not a binary fact but an inference under uncertainty (Arinze et al., 2024; Charoenthammachoke et al., 2020).

The operational decision pipeline is therefore central. A batch must be accepted or rejected, sometimes with rework options, based on imperfect evidence. If acceptance rules are too permissive, defect escape risk increases and consumer exposure grows, which can lead to complaints and recalls; if rules are too conservative, false rejection increases and batch release slows, reducing supply continuity and increasing cost, which can also drive risky workarounds such as rework beyond validated limits (Fonseca & Azevedo, 2020; Frederico et al., 2021).

The reliability challenge is exacerbated by the fact that some defect modes are latent: microbial issues may not be detected in early screening but can manifest later if preservation is marginal; phase separation may occur after thermal cycles in logistics; packaging leaks may appear only after handling stress; and color drift may become noticeable under specific lighting conditions. These defects are not necessarily detectable by a single test; rather, they are best managed through a structured system of incoming material control, in-process monitoring, stratified sampling, accelerated stability checks, and governed release decisions that account for risk profiles (Namdar et al., 2021; Shehun, 2022).

Many beauty manufacturers respond to quality incidents by adding tests, increasing sampling, or imposing longer hold times, but these actions can degrade throughput and still fail to reduce defect escape if they are not targeted to the dominant uncertainty sources and failure mechanisms (Aki, 2017; Hasan, 2024). For example, increasing the number of viscosity measurements may not help if the dominant issue is sampling bias in a poorly mixed tank, and increasing microbial testing volume may not reduce risk if the dominant issue is environmental contamination during filling that is not captured by batch sampling. An engineering approach is needed that frames cosmetics quality as a decision reliability problem, models uncertainty propagation through the QC pipeline, and evaluates alternative architectures using metrics that connect laboratory decisions to field outcomes such as complaint incidence and returns (John, 2019; Păunescu et al., 2018).

This article develops such a framework and demonstrates it using a scenario-based quantitative study across three representative cosmetic product categories: an emulsion-based skin-care product with viscosity and phase stability risk, a preservative-limited "clean beauty" formulation with elevated microbial and odor risk, and a color cosmetic with shade consistency and dispersion risk.

Four operational QC architectures are compared: Architecture A baseline end-of-line testing and release; Architecture B increased test density without governance changes; Architecture C risk scoring combining multiple indicators but with limited drift and sampling governance; and Architecture D a two-tier governed approach using stratified sampling, drift-aware measurement controls, stage-gated release with accelerated checks, and nuisance-constrained decision thresholds. The study asks which uncertainty sources dominate defect escape and complaint risk, how architectures trade false rejection against escape, and which governance principles provide the strongest reliability improvement without eroding supply continuity.

2. LITERATURE REVIEW

Cosmetic quality assurance literature and industry practice emphasize specification-based release and stability testing, yet applied reliability challenges increasingly arise from the combination of high product variety, short development cycles, and complex supply chains that create variability beyond what static specifications capture (Magableh, 2021; Tirkolaee et al., 2021). Many quality failures are multi-causal and are triggered by interactions between ingredient variability, processing history, packaging, and distribution conditions, suggesting that defect escape cannot be reduced simply by tightening single-parameter limits without increasing false rejection (Ishida, 2020). This supports a reliability view where specifications and tests must be combined into a governed decision system, and where sampling and measurement uncertainty must be treated explicitly.

Stability and compatibility are central reliability domains, because phase separation, viscosity drift, and odor changes often emerge under thermal cycling and time, and accelerated stability tests act as early-warning evidence (Lee et al., 2019; Mittal, 2023). Accelerated tests consume time and can increase batch release latency, meaning that programs must decide which products require stronger pre-release evidence and which can rely on ongoing stability monitoring. Microbial risk is similarly governed by preservative robustness and hygienic design; testing can detect contamination, but prevention and environmental monitoring reduce occurrence, and the decision pipeline must balance sensitivity with operational feasibility. For color cosmetics, shade consistency and dispersion are primary, and measurement systems such as colorimetry offer quantitative control, yet visual perception and lighting variability mean that acceptance must consider perceptual tolerances and process capability, not only nominal coordinates (Shishodia et al., 2019; Zeng et al., 2016).

The applied gap motivating this study is the limited availability of integrated, engineering-quantitative frameworks that connect QC design choices to defect escape probability, release latency distributions, complaint risk, and cost, while explicitly modeling uncertainty in sampling and measurement. This article addresses that gap by modeling cosmetics QA as a decision system and comparing operational architectures under production-relevant metrics (Azadegan et al., 2020; Gu et al., 2023; Suresh et al., 2020).

3. METHOD

Scenario Design and Defect Modes

Three product scenarios are modeled: Scenario 1 emulsion skin-care where primary defects are viscosity out-of-spec and phase separation; Scenario 2 preservative-limited formulation where defects include microbial contamination proxy exceedance and off-odor risk; Scenario 3 color cosmetic where defect is shade mismatch beyond perceptual tolerance and pigment dispersion variability. Each batch is characterized by latent quality parameters influenced by raw material variability and process variability. Defects become "escape-critical" if they exceed defined thresholds that would plausibly trigger consumer dissatisfaction or safety concern.

Measurement Uncertainty and Sampling Model

Lab measurements (viscosity, pH, microbial proxy, color coordinates) include random error and bias drift, and sampling includes within-tank heterogeneity modeled as a spatial variance component. Stratified sampling reduces variance by taking samples from multiple locations. Accelerated stability checks provide additional evidence with time delay.

QC Architectures and Release Decisions

Architecture A uses standard end-of-line tests and release if all measured values are within limits. Architecture B increases test count and sampling but retains fixed decision rules. Architecture C computes a risk score combining multiple indicators and uses a threshold for hold or release, but drift governance is limited. Architecture D uses two-tier governance: tier-1 evidence triggers provisional release for low-risk products under enhanced field monitoring, while tier-2 evidence is required for high-risk products before release; it uses nuisance-constrained thresholds, drift checks, stratified sampling for high-variance products, and limited accelerated stability gating for critical risk categories.

Metrics

Outcomes include defect escape probability, false rejection probability, median and 90th percentile time-to-release, complaint incidence risk proxy, and expected cost index per batch.

4. RESULT AND DISCUSSION

A monitoring or test strategy can reduce defect escapes, but it may do so at the expense of higher false rejection, longer release cycles, or both. These side effects matter operationally because false rejects consume rework capacity and scrap budget, while release latency directly reduces throughput and delivery reliability. Table 1 therefore evaluates the four architectures using three decision-critical outcomes: the weighted probability of defect escape across scenarios, the probability of false rejection, and the distribution of time-to-release, reported through median and 90th percentile values to capture both typical and tail delays.

Table 1. Defect escape, false rejection, and release latency

Metric	A Baseline	B More tests ungoverned	C Risk scoring	D Two-tier governed
Defect escape probability (all scenarios, weighted)	0.012	0.010	0.007	0.004
False rejection probability	0.021	0.038	0.024	0.020
Median time-to-release (hours)	26	33	28	27
90th percentile time-to-release (hours)	61	92	73	58

Source: data proceed

Table 1 indicates that simply adding tests without governance can reduce defect escape slightly, but at the cost of significantly higher false rejection and much longer release tails, which in a beauty supply chain translates directly into stockouts, expedited logistics, and pressure to rework or override holds, all of which can undermine the intended quality benefit. Risk scoring improves escape probability without inflating false rejection as severely because it uses combined evidence rather than multiple independent pass-fail gates, yet release tails remain high when drift and sampling heterogeneity generate ambiguous risk scores that trigger holds.

The governed two-tier architecture yields the lowest defect escape while keeping false rejection near baseline and compressing release tails because it targets stronger evidence to higher-risk products and uses nuisance-constrained thresholds and stratified sampling to reduce ambiguity, thereby improving decision stability without imposing unnecessary holds across all products.

Table 2. Scenario-wise complaint risk proxy and dominant defect drivers

Scenario	Dominant defect mode	Complaint risk proxy with A	Complaint risk proxy with D	Reduction factor
Emulsion skin-care	Viscosity drift, phase instability	1.00	0.66	1.5×
Preservative-limited	Microbial proxy, odor change	1.00	0.58	1.7×
Color cosmetic	Shade mismatch, dispersion	1.00	0.62	1.6×

Source: data proceed

Table 2 shows that the two-tier governed approach reduces complaint risk consistently across scenarios, but the mechanism differs by defect mode, illustrating why cosmetics QA cannot rely on one-size-fits-all testing. For emulsions, stratified sampling and process-history-aware governance reduce the probability that a localized mixing deficiency is missed by a single sample, and stage-gated release using short accelerated checks filters marginal stability cases that would otherwise escape.

For preservative-limited products, governance reduces risk primarily by reducing decision latency variance and improving drift detection in microbial proxy measurements, so that marginal preservative performance is identified earlier and held consistently rather than being released due to measurement bias. For color cosmetics, combining quantitative colorimetry with governed acceptance rules aligned to perceptual tolerance reduces both over-rejection and escapes, because it avoids letting minor instrument noise trigger holds while still catching true dispersion-related shade shifts that consumers notice, demonstrating the benefit of interpreting measurements through a reliability-governed decision model.

Table 3. Cost and operational sustainability index

Metric	A Baseline	B More tests ungoverned	C Risk scoring	D Two-tier governed
QC workload index (normalized)	1.00	1.42	1.12	1.15
Field complaints and returns cost index	1.00	0.88	0.73	0.55
Total expected cost index	1.00	1.19	0.93	0.86

Source: data proceed

Table 3 confirms that the economic objective is not to maximize testing, but to minimize total expected cost by balancing QC workload, release latency, and field failure costs. The ungoverned increase in testing increases workload and delays strongly enough that total cost rises despite some reduction in complaints, which is consistent with real beauty operations where slow release creates service penalties and rush behavior that can reintroduce risk.

Risk scoring reduces field costs while keeping workload moderate, but the best performance is achieved by the governed two-tier approach because it reduces defect escape most effectively while maintaining stable operations; importantly, its workload index is slightly higher than baseline because it reallocates effort into stratified sampling and drift checks, yet this effort yields a larger reduction in field failure cost, which dominates the total cost and drives the improved reliability outcome.

Table 3 provides a compact but revealing view of why governance, not volume, determines whether a QC program is economically sustainable. The QC workload index represents the internal burden associated with inspection, testing, review, verification, and disposition activities. Architecture B increases this burden substantially to 1.42, indicating that ungoverned test expansion creates a large operational load. In practice, this load is not merely "more work"; it also changes the dynamics of decision-making. When review queues grow, release decisions slow down, the organization becomes more likely to batch decisions rather than resolve them promptly, and the system becomes vulnerable to backlog-driven behaviors such as rushed sign-off, inconsistent interpretation, or informal bypass of low-trust alarms. These behaviors are well documented in other safety-

critical operational domains and are consistent with the broader argument that alarm and hold volume can erode decision reliability when it exceeds human and organizational capacity.

The field complaints and returns cost index captures the downstream consequences of defects that escape the factory or are discovered late by customers. Here, Architecture B does reduce field cost relative to the baseline (0.88), which is expected because more tests catch more issues. However, the key insight is that the reduction is not large enough to compensate for the internal burden and the secondary effects of slower release. As a result, total expected cost rises to 1.19, making Architecture B economically inferior despite being "stricter." This is a classic quality-economics outcome: once testing begins to overload the system, the marginal benefit of additional detection is outweighed by the marginal cost of delay, congestion, and operational instability. Put differently, the organization pays for quality twice, first through expanded inspection effort and then again through degraded throughput and decision speed.

Architecture C shifts the system from brute-force inspection toward risk scoring, and the cost indices reflect that change. Workload increases only modestly to 1.12, while field complaints and returns costs drop to 0.73. The net effect is a total expected cost reduction to 0.93, suggesting that risk scoring improves discrimination: it concentrates attention on parts, builds, or lots that are more likely to be defective and avoids spending equal effort on low-risk material. This is the beginning of an efficient frontier: modest additional internal effort produces a relatively large reduction in expensive external failures, it also indicates improved sustainability because the QC function remains within a manageable workload range where engineers and inspectors can respond consistently, rather than operating in perpetual overload.

The strongest result appears in Architecture D, the two-tier governed approach. Its workload index (1.15) is slightly higher than risk scoring alone, reflecting the fact that governance introduces structured activities such as stratified sampling, drift checks, confirmation tiers, and escalation pathways. Importantly, this "extra work" is not waste. It is targeted work that improves the integrity of the decision pipeline. The payoff is clear: field complaints and returns costs fall sharply to 0.55, and total expected cost falls to 0.86, the best performance among all architectures. This pattern suggests that the cost structure is dominated by field failure costs, which is typical in many high-consequence production environments where external failures trigger not only returns but also service penalties, warranty costs, customer churn, and reputational harm. When downstream costs dominate, the economically rational strategy is not minimal QC workload; it is reliable prevention of escapes, provided internal operations remain stable.

A deeper implication is that the relationship between workload and total cost is non-linear. Architecture B demonstrates that workload growth can cross a threshold beyond which the system becomes congested and unstable, causing total cost to increase. Architectures C and D demonstrate a different regime: moderate workload increases that remain within capacity can be highly cost-effective when they reduce escape probability and the long-tail of expensive field events. In other words, sustainability is not achieved by minimizing QC effort; it is achieved by keeping QC effort in a range where it produces high-value detection and prevention without triggering congestion effects (Kusumawardani et al., 2024; Panitsettakorn et al., 2023). Two-tier governance seems to place the system in that favorable regime by ensuring that high-intensity verification is reserved for high-risk cases while low-risk material flows with minimal delay.

Another important interpretive point is that the workload index should not be read as an absolute negative. A workload index slightly above baseline can be optimal if it represents better allocation of effort rather than unnecessary activity. The two-tier governed model reallocates work from broad, low-yield testing to high-yield confirmation and drift monitoring. Drift checks, in particular, often look like overhead, but they prevent false stability, where the organization believes performance is steady while sensors or process conditions slowly shift toward a boundary. Preventing false stability reduces the frequency of "surprise" field failures that are typically the most expensive and reputation-damaging, and it also prevents the kind of reactive firefighting that is itself unsustainable.

Table 3 reinforces a governance lesson that is easy to miss when focusing narrowly on defect detection: economic performance depends on operational behavior and decision latency. An ungoverned expansion of testing can create delays that force rushed shipments, delayed releases, or inconsistent dispositions, which can reintroduce risk even as inspection increases. A governed system can create a stable operating rhythm in which alerts are credible, workloads are bounded, and decisions are timely. Stability of decision-making is itself a cost reducer because it prevents queueing cascades, reduces rework churn, and supports predictable release cycles that align with production planning and customer commitments (Ardi et al., 2024; Chowdhury et al., 2020; Guntuka et al., 2024).

The table supports the conclusion that the optimal QC strategy is one that minimizes total expected cost by explicitly managing the trade-off between internal QC burden and external failure consequences. Architecture B illustrates that "more testing" can be financially harmful when it is ungoverned, while Architecture C shows that risk scoring improves cost efficiency by targeting resources. Architecture D delivers the best economic and sustainability performance because it couples risk scoring with tiered verification and drift governance, reducing defect escapes and costly field outcomes while maintaining internal workload at a level that remains operationally sustainable.

5. CONCLUSION

Quality reliability in the beauty industry is best understood as an end-to-end decision reliability problem because defect escape, complaint cascades, and supply disruptions depend on how sampling and measurement uncertainty propagate through batch release decisions and how release holds and interventions are governed under throughput pressure. The scenario-based comparative analysis demonstrates that expanding tests without governance can increase false rejection and release latency tails, undermining supply continuity and potentially provoking risky workarounds, while only modestly reducing defect escape. A risk-scoring approach improves defect escape outcomes but remains sensitive to drift and sampling heterogeneity unless explicitly governed. A two-tier governed architecture that uses stratified sampling for high-variance products, drift-aware measurement controls, nuisance-constrained thresholds, and stage-gated release aligned with product risk reduces defect escape and complaint risk while stabilizing time-to-release distributions and minimizing total expected cost.

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