The Practitioner's Guide to

LEADING vs. LAGGING QUALITY INDICATORS

How to Measure What Predicts Quality Outcomes Instead of Only Measuring What Already Happened

Including a Complete Case Study: Ardmore Electronics Manufacturing

Quality Engineering Series

Measuring What Has Happened vs. Measuring What Is About to Happen

Every manufacturing quality management review involves a version of the same ritual: a team gathers, a dashboard is displayed, and a series of numbers are reviewed — defect rates, customer complaints, scrap percentages, audit findings, warranty claims. These numbers are discussed, compared to prior periods and targets, explained when they are bad and acknowledged when they are good. Actions are assigned. The meeting ends.

This ritual has a fundamental structural problem. Every single metric in that standard dashboard is a lagging indicator — a measurement of what has already happened. The defects have already been produced. The customer has already complained. The scrap is already in the bin. The audit has already found the findings. By the time these numbers appear on the dashboard, the events that created them are history. The quality management system is conducting a thorough post-mortem on outcomes it had no ability to prevent because it was not measuring the conditions that produce those outcomes until after they occurred.

Leading quality indicators work differently. They measure process inputs, conditions, and behaviors that precede and predict quality outcomes — measurements taken upstream of the failure, at a point in time when there is still an opportunity to intervene. A leading indicator showing that preventive maintenance completion rates have dropped three weeks before a machine-caused defect spike gives quality leadership time to respond. A lagging indicator showing that the defect rate spiked does not.

The distinction between leading and lagging indicators is not merely conceptual. It is one of the most consequential choices in quality metric system design — determining whether a quality program can prevent problems or can only react to them. This guide provides a complete treatment of both: what they are, what each is good for, how to design a balanced measurement system that uses both intelligently, and how to identify and validate the leading indicators that actually predict the outcomes your organization cares about most.

What This Guide Covers

The fundamental difference between leading and lagging indicators — with manufacturing-specific examples of each

Why lagging-only dashboards are structurally incapable of preventing quality failures

How to identify genuine leading indicators that predict your specific quality outcomes

Validating the predictive relationship — how to know if a leading indicator actually leads

Designing a balanced measurement architecture that uses both types effectively

Case Study: Ardmore Electronics Manufacturing — from a lagging-only dashboard to a predictive quality system

Common mistakes in leading indicator design and how to avoid them

Quick Reference: indicator design guide, manufacturing examples library, and a balanced scorecard template

Section 1: The Fundamental Distinction

LEADING INDICATORS	LAGGING INDICATORS

What Lagging Indicators Actually Measure

Lagging indicators measure outcomes — the results of processes that have already completed. They tell you what happened. In quality management, the most common lagging indicators include:

- Internal defect rate / parts per million (PPM)
- Customer complaint rate / customer-reported defects
- Scrap and rework costs
- First-pass yield
- Warranty claims and field returns
- Audit findings (internal and external)
- Customer satisfaction scores
- CAPA volume and aging

These are all legitimate and important measurements. They confirm that a quality problem occurred, quantify its magnitude, and provide historical trend data. What they cannot do is tell you the problem is about to occur — because by definition, the measurement only becomes available after the outcome has been produced.

The temporal gap between a quality event and its appearance in a lagging indicator is not trivial. A machine condition that begins deteriorating in January may not appear in the defect rate until February and may not appear in a customer complaint until March. A procedure compliance issue that begins in Q1 may not appear in an audit until Q3. A material quality problem that enters the supply chain in week one may not appear as a warranty claim for months. During all of that time, the lagging measurement system is providing no signal — it has nothing to report because the outcome has not yet registered.

What Leading Indicators Actually Measure

Leading indicators measure process inputs, conditions, and behaviors that occur before quality outcomes are produced — at a point in time when those outcomes are still preventable. A genuine leading indicator has a demonstrated predictive relationship with a specific quality outcome: when the leading indicator moves in a particular direction, the quality outcome tends to follow, after a predictable time lag. Examples:

- Preventive maintenance completion rate (leads: machine-caused defect rate)
- Standard work adherence rate (leads: process-related defect rate)
- Gauge calibration currency — percent of gauges within calibration interval (leads: measurement error rate and associated quality escapes)

- Operator training and certification currency (leads: skill-related error rate)
- In-process statistical process control out-of-control signal rate (leads: specification non-conformance at final inspection)
- Supplier incoming inspection rejection rate by material lot (leads: process yield on production runs using that material)
- Near-miss and deviation reporting rate (leads: quality escape rate — higher near-miss reporting correlates with lower escape rate as problems are caught earlier)
- Process parameter adherence rate — proportion of production cycles executing within defined parameter windows (leads: process-caused defect rate)

> **The Critical Distinction**
> *A lagging indicator says: 'Here is what quality looked like last week.'*
> *A leading indicator says: 'Here is what quality will probably look like next week — and here is your opportunity to change it.'*
> *The purpose of lagging indicators is accountability and trend tracking. The purpose of leading indicators is prediction and prevention. Both are necessary. A quality management system that has only lagging indicators is structurally positioned to do one thing: respond to quality failures after they occur.*
> *The question every quality leader should ask about their measurement system: 'Of the metrics we review regularly, how many give us an opportunity to prevent a problem? How many only tell us a problem has already happened?'*

A Direct Comparison

Dimension	Lagging Indicators	Leading Indicators
What they measure	Outcomes — results of processes that have completed	Inputs and conditions — factors that precede and produce outcomes
When the data is available	After the quality event has occurred	Before the quality event occurs — while there is still time to intervene
Primary value	Accountability, trend tracking, historical analysis, regulatory compliance	Prediction, prevention, early warning, proactive management
Management action enabled	Reactive: investigate what happened, assign corrective actions, communicate performance	Proactive: intervene in conditions before they produce failures
Ease of measurement	Relatively easy — outcomes are observable and countable	Requires process design — must identify what to measure and build measurement into the process
Risk of gaming	Moderate — outcome metrics can be manipulated through inspection intensity and escape tolerance	Higher — process compliance metrics can be gamed if compliance is reported rather than measured
Connection to outcome	Direct — the outcome IS the metric	Indirect — requires a demonstrated predictive relationship to the outcome

Dimension	Lagging Indicators	Leading Indicators
Examples in manufacturing	Defect rate, scrap cost, customer complaints, audit findings, warranty rate	PM completion rate, SPC adherence, calibration currency, near-miss report rate, process parameter compliance

Why Most Quality Dashboards Are Almost Entirely Lagging

The preponderance of lagging indicators in manufacturing quality measurement systems is not an accident. It reflects several structural realities that push measurement systems toward outcome measurement and away from predictive measurement:

Structural Force	Why It Produces Lagging-Heavy Systems
Outcomes are observable	Defects, customer complaints, and warranty claims are visible, countable, and unambiguous. Process conditions that predict future defects are less visible — they require instrumentation, structured observation, and deliberate measurement design. Outcome measurement is natural; condition measurement is designed.
Regulatory requirements are outcome-based	ISO 9001, IATF 16949, FDA QSR, and most industry-specific quality standards specify outcome measurement requirements: nonconformance rates, corrective action records, customer complaint processes. They create measurement obligations for outcomes and rarely mandate specific leading indicator measurement.
Accountability systems are outcome-oriented	Management reporting, performance reviews, and organizational accountability conversations are structured around results. 'Quality is 3.2% defects this quarter' is a straightforward accountability statement. 'PM completion rate was 87% this quarter' is a process compliance statement — less directly connecting to anyone's performance evaluation.
Leading indicator design requires domain knowledge	Selecting a valid leading indicator requires understanding the causal mechanism that connects the input measurement to the output outcome — understanding that a specific type of equipment condition leads to a specific type of defect, that specific process parameter ranges predict specific yield degradation. This requires deeper process knowledge than outcome measurement, which is simply counting what already happened.
Validation requires longitudinal data	Confirming that a proposed leading indicator actually predicts the intended outcome — rather than merely being associated with it coincidentally — requires analyzing the relationship between the indicator and the outcome over time. Organizations that have been measuring outcomes but not process conditions have no historical data from which to validate leading indicator candidates.

Section 2: Identifying Genuine Leading Indicators

The most important — and most commonly misunderstood — aspect of leading indicator design is that not every upstream metric is a genuine leading indicator. A leading indicator must have a demonstrated, causal predictive relationship with the outcome it is supposed to lead. Without this relationship, measuring it provides no advance warning and creates measurement overhead without management value.

The Three Requirements of a Valid Leading Indicator

#	Requirement	What It Means in Practice
1	**Precedence**	The leading indicator must change before the quality outcome changes. If PM completion drops in week 3 and machine-caused defects increase in week 5, PM completion is temporally precedent to the defect outcome. If both change simultaneously, the 'leading' indicator is actually concurrent — it tells you the same thing as the lagging indicator, just in different units.
2	**Causal plausibility**	There must be a plausible mechanism by which the leading indicator causes or contributes to the quality outcome. PM completion affects machine-caused defects because deferred maintenance produces equipment wear that generates dimensional drift. This mechanism is physically plausible and independently verifiable. A statistical correlation without a plausible mechanism may be coincidental rather than causal — and will not reliably predict when operating conditions change.
3	**Actionability**	The leading indicator must change in a direction that allows management action before the quality outcome occurs. If the indicator changes but there is nothing that can be done between the indicator signal and the outcome that would prevent the outcome, the indicator provides information but not prevention opportunity. A gauge that measures incoming material that has already been committed to production and cannot be returned is less actionable than one that flags material before it enters the production schedule.

The Causal Chain Method: Working Backward from Quality Outcomes

The most reliable method for identifying valid leading indicators is to start with a specific quality outcome — a defect type, a failure mode, a quality escape — and work backward through the causal chain until you reach measurable upstream inputs. This approach ensures that the leading indicators selected have a direct causal connection to the outcomes they are intended to predict.

Step in the Method	Example: Solder Joint Defect Rate
Step 1: Define the specific quality outcome to be predicted. Be precise — 'quality problems' is too broad; 'solder joint opens at reflow' is specific.	Target outcome: solder joint opens (opens and bridging) at wave solder, measured by in-circuit test failure rate.

Step in the Method	Example: Solder Joint Defect Rate
Step 2: Identify the immediate process step(s) that produce this outcome. What specific operation creates this defect?	Immediate cause: wave solder process — solder temperature, conveyor speed, flux density, and wave height are the critical parameters.
Step 3: Identify the controllable inputs to that process step. What factors determine whether that step produces a conforming or non-conforming output?	Solder bath temperature (must be 250°C ±5°C); flux application coverage and density; conveyor speed (determines dwell time in solder); solder bath contamination level (copper and tin impurity concentration).
Step 4: Identify what can be measured before the process step executes that would predict the step's output. This is your leading indicator candidate.	Leading indicator candidates: (a) solder bath temperature stability in the 2 hours before production run; (b) flux specific gravity measurement before each shift; (c) last solder bath contamination assay result; (d) conveyor speed verification at changeover.
Step 5: Validate the predictive relationship. Does historical data show that leading indicator degradation precedes outcome degradation?	Validate by: correlating past flux specific gravity readings with same-shift solder joint defect rates; correlating solder bath contamination levels with subsequent week's defect rates; reviewing whether defect spikes were preceded by parameter deviations.

⚠ Not All Upstream Metrics Are Leading Indicators

A common mistake is assuming that any metric measured before the final inspection is a leading indicator. The test is the predictive relationship — does this metric, when it changes, reliably precede a change in the quality outcome?

Activity metrics are particularly prone to this confusion. 'Number of training sessions conducted' is upstream of quality but is not a leading indicator of quality unless a validated relationship exists between training activity and quality outcomes. 'Operator certification currency' (the proportion of operators whose certification is current) is a better leading indicator candidate because there is a plausible causal mechanism: operators with lapsed certifications are more likely to execute procedures incorrectly.

Always ask: 'If this metric improves, do we expect the quality outcome to improve — and why?' If the answer is vague or speculative, the metric is not yet a validated leading indicator.

Validating the Predictive Relationship

Selecting a leading indicator candidate based on causal logic is the first step. Validating that the candidate actually predicts the intended outcome — in your specific process, with your specific materials and equipment — is the second and equally important step. Validation methods range from simple to rigorous:

Validation Method	How to Apply It
Historical correlation analysis	If historical data exists for both the proposed leading indicator and the outcome, plot both time series and assess whether changes in the leading indicator consistently precede changes in the outcome by the expected time lag. Simple correlation over rolling windows can quantify the relationship. A leading indicator candidate that correlates at 0.3 or lower with the intended outcome over the historical period should be reconsidered.
Stratified outcome analysis	Group outcome data by leading indicator levels — periods when the leading indicator was high vs. low, compliant vs. non-compliant — and compare outcome rates between groups. If the outcome rate is substantially different between groups (e.g., defect rate is 2× higher in periods when PM completion was below target), the predictive relationship is supported.
Prospective tracking	Begin measuring the leading indicator candidate and track whether its movements precede outcome changes going forward. This is slower than historical analysis but provides real-time validation under current process conditions. After 3–6 months of parallel data collection, assess whether the expected predictive relationship is observable.
Subject matter expert triangulation	Consult with process engineers, maintenance mechanics, and experienced operators about whether they observe a relationship between the proposed leading indicator and the outcome in their day-to-day work. 'When the flux specific gravity is off, does that shift typically show more solder defects?' This qualitative validation complements quantitative analysis and often reveals mechanisms that data analysis cannot.
Controlled trials	When feasible and safe, deliberately vary the leading indicator within acceptable bounds and measure the effect on the outcome. This is essentially a designed experiment — the gold standard for establishing causality rather than correlation. Feasibility depends on whether controlled variation of the indicator is ethically acceptable (it usually is for process parameters but not for safety-related conditions).

The Time Lag: Understanding Predictive Horizons

Every genuine leading indicator has a time lag — the typical delay between a change in the leading indicator and the corresponding change in the quality outcome. Understanding this time lag is essential for designing effective monitoring systems and intervention protocols.

A leading indicator with a very short time lag (hours to a day) provides early warning but limited response time. A leading indicator with a longer time lag (days to weeks) provides more response time but may also be less precise — many things can happen between the indicator signal and the outcome that complicate the predictive relationship.

Leading Indicator	Typical Time Lag	Response Opportunity
SPC out-of-control signal on critical dimension	Hours to same shift	Stop production, investigate root cause, adjust process before producing additional out-of-tolerance parts

Leading Indicator	Typical Time Lag	Response Opportunity
Coolant concentration out of specification	Hours to 1–2 days	Adjust coolant before tool wear accelerates and produces dimensional drift
Process parameter deviation from standard (temperature, pressure, speed)	Minutes to hours (current run)	Immediate adjustment prevents current run defects; investigation prevents recurrence
Preventive maintenance task overdue	Days to weeks	Complete PM before equipment condition deteriorates to defect-producing level
Operator certification expired	Days to weeks	Schedule and complete refresher before certification gap produces skill-related error
Supplier incoming material near specification limit	Production run to run	Flag material for enhanced monitoring; alert production planning; consider material hold before borderline material enters process
Declining near-miss reporting rate	Weeks to months	Investigate why near-miss reporting has declined (fear of consequences, leadership disengagement) before the reporting gap produces an undetected escape
Calibration interval overdue on critical measurement instruments	Days to weeks	Complete calibration verification before measurement error produces undetected out-of-tolerance parts

Section 3: Designing a Balanced Measurement System

The goal is not to replace lagging indicators with leading indicators — both serve essential and different purposes. The goal is to design a measurement architecture that uses each type for what it is best suited for, creates clear linkages between leading indicators and the outcomes they predict, and enables a quality management system that is genuinely preventive rather than merely reactive.

The Measurement Architecture Principle: Causal Alignment

A balanced measurement system pairs each important lagging indicator with at least one validated leading indicator that predicts it. The pairing is not arbitrary — it is based on the causal chain analysis described in Section 2. The result is a measurement architecture in which every outcome measurement has a corresponding process condition measurement, and management knows which inputs to monitor to predict each output.

Lagging Indicator (What Happened)	Validated Leading Indicator(s) (What Predicts It)	Management Action When Leading Indicator Signals
Machine-caused dimensional defect rate	PM completion rate; bearing wear measurement at PM; coolant concentration	Complete overdue PM; replace worn bearings before defect threshold; adjust coolant
Solder joint defect rate	Solder bath temperature stability; flux specific gravity; solder contamination assay	Adjust bath temperature; replace flux; perform solder bath refresh before production run
Operator-caused assembly error rate	Standard work adherence rate (Gemba observation); certification currency	Coach to standard; schedule recertification; investigate why adherence dropped
Material-caused process yield	Incoming material property measurements vs. specification limits; supplier quality incident rate	Flag marginal material; enhance in-process monitoring; notify supplier; review production plan
Customer complaint rate	Final inspection detection rate; escaped-defect-at-station rate; SPC signal rate at final	Enhance inspection at stations with declining detection rates; address SPC signals before release
Quality escape rate (shipped defects)	Near-miss reporting rate; in-process first-pass yield by station; detection coverage audit score	Investigate near-miss decline; strengthen detection at low-yield stations; audit detection gaps

Tiered Measurement: Strategic, Operational, and Real-Time

A well-designed measurement system operates at three tiers simultaneously, with different measurement frequencies and audiences at each tier:

Tier	Audience & Frequency	Lagging Indicators	Leading Indicators
Strategic (Monthly/Quarterly)	Plant manager, quality director, senior leadership — monthly review	Customer complaint rate; warranty rate; audit findings; quality cost as % of revenue; supplier quality scorecard	Supplier approval program health; CAPA effectiveness rate; quality training completion rate; preventive action rate vs. corrective action rate
Operational (Weekly)	Quality manager, manufacturing manager, engineering team — weekly review	Internal defect rate by line; scrap and rework cost; first-pass yield; CAPA cycle time	PM completion rate; calibration currency; SPC out-of-control rate; process parameter compliance; near-miss report rate; operator certification currency

Tier	Audience & Frequency	Lagging Indicators	Leading Indicators
Real-Time (Shift / Daily)	Team leaders, operators, quality technicians — shift start and continuous	Shift defect count; first-article rejection rate; in-process reject rate by station	SPC chart status by machine; process parameter verification at startup; tooling condition flag; setup verification completion

> **The Ratio Target**
>
> *A quality measurement system that is performing its preventive function should have more leading indicators than lagging indicators in its operational and real-time tiers — roughly a 60/40 or 70/30 leading-to-lagging ratio in the metrics reviewed at team leader and operator level.*
>
> *At the strategic level, lagging indicators are appropriate to dominate — executives need to know outcomes. But at the operational and real-time levels, a lagging-heavy measurement system is structurally incapable of enabling the daily prevention that those tiers of the organization are positioned to perform.*
>
> *If your operational dashboard is 80% lagging indicators, your quality system is structurally reactive at the operational level. The people who could prevent problems are only being told when problems have occurred.*

How to Review Leading Indicators Effectively

The way leading indicators are reviewed in management meetings matters as much as the indicators themselves. A leading indicator that is reported, noted, and then moves on to the next agenda item without generating a decision or action is not functioning as a preventive tool — it is functioning as an activity report. These review disciplines distinguish effective leading indicator use from performative measurement:

Review Discipline	What It Looks Like
Threshold-based response	Each leading indicator has a pre-defined threshold that, when crossed, triggers a specific management response — not a discussion about whether to respond, but an automatic escalation or action. PM completion below 85% triggers an automatic PM scheduling review. Flux specific gravity outside range triggers a flux replacement before the next shift. The response is designed when the indicator is designed, not at the review meeting.
Trend review, not point review	A single data point rarely tells a meaningful story. Leading indicators should be reviewed as time series — is the indicator trending toward a threshold? Has it been hovering near a threshold for multiple periods? A PM completion rate of 87% this week is less concerning than a PM completion rate that has been declining from 95% to 92% to 89% to 87% over four weeks, even though the current reading is above threshold. Trend analysis is what provides genuine early warning.
Connection to prediction	When a leading indicator signals, the review should explicitly reference the predicted lagging outcome: 'PM completion has been below 85% for three

Review Discipline	What It Looks Like
	weeks. Based on our historical data, we typically see a 40% increase in machine-caused defects within two to three weeks of sustained PM under-completion. We need to complete the overdue PMs this week.' This connection sustains the organizational understanding that the leading indicator is predictive, not just reportable.
Action assignment before moving on	Every leading indicator that is outside target generates an assigned action — who will do what by when. No leading indicator signal is discussed and moved on from without an action assigned. This discipline is what separates a measurement system that drives improvement from one that tracks information.
Verification that the action worked	At the next review, confirm: (a) was the assigned action completed, (b) did the leading indicator return to acceptable range, and (c) did the lagging outcome remain within acceptable range? This three-part verification closes the loop between leading indicator signal, management action, and outcome confirmation — building organizational confidence in the predictive system over time.

Section 4: Case Study — Ardmore Electronics Manufacturing

Company Background

Ardmore Electronics Manufacturing (AEM) is a fictional contract electronics manufacturer (CEM) producing printed circuit board assemblies (PCBAs) and complete electronic sub-assemblies for the telecommunications, industrial automation, and medical device industries. AEM operates a 145,000 square foot facility with SMT (surface mount technology) lines, wave solder lines, selective solder equipment, and a full inspection suite including automated optical inspection (AOI), X-ray, and in-circuit test (ICT). The company employs 390 people across two shifts and maintains ISO 9001 and IPC-A-610 Class II/III certifications.

AEM had experienced two years of declining quality performance. The internal defect rate at final test had increased from 1.8% to 3.4%. Three customer quality escapes in an 18-month period had resulted in a significant customer placing AEM on a formal corrective action requirement, and a second customer had initiated a supplier qualification review. The quality director, Kenji Murakami, was under significant organizational pressure to demonstrate a credible improvement plan.

The Assessment: What AEM's Quality System Was and Wasn't Measuring

Kenji began his assessment by cataloguing every quality metric in AEM's existing measurement system. The audit produced the following distribution:

Metric Type	Metrics in the Current System
Lagging — strategic	Customer complaint rate; warranty / field return rate; customer escapes per quarter; first-pass yield; external audit findings count
Lagging — operational	Internal defect rate at ICT; defect rate by defect category; scrap and rework cost; CAPA open count and aging; solder joint defect rate; ICT failure rate; AOI false-call rate
Lagging — real-time	Shift defect count; station reject rate; first-article rejection count; rework center queue depth
Leading — operational	None formally tracked. PM completion was tracked by maintenance but not reviewed by quality management. Calibration records were maintained but not summarized as a percentage-current metric.
Leading — real-time	SPC charts existed on three critical solder parameters but were maintained manually and reviewed inconsistently. No formal process for escalating SPC out-of-control signals existed.

The picture was stark: AEM's quality measurement system was almost entirely lagging indicators. The organization was reviewing quality outcomes comprehensively but had essentially no measurement of the process conditions that produced those outcomes. The quality management system could describe what had happened to quality in detail. It had no mechanism for predicting or preventing what was about to happen.

Identifying the Leading Indicators: The Causal Chain Analysis

Kenji convened a cross-functional team — quality engineers, process engineers, the maintenance manager, and senior operators from SMT and wave solder lines — for a two-day causal chain analysis workshop. The objective was to identify the inputs and conditions that predicted each of AEM's three major defect categories: solder joint defects (42% of all defects), component placement defects (31%), and inspection detection failures (27%).

Causal Chain 1: Solder Joint Defects

Working backward from solder joint defect rate, the team identified the process conditions that most directly determined solder joint quality:

- Wave solder bath temperature: historical data showed that bath temperature deviation of more than 3°C from nominal preceded elevated solder joint defect rates within the same production shift
- Flux application density and specific gravity: operators reported that shifts following a flux cartridge change or mixing error frequently produced elevated bridging rates
- Solder bath contamination (copper content): the team identified that AEM's solder contamination assay was performed monthly but that the relationship between contamination level and defect rate had never been analyzed
- Conveyor speed verification: a review of defect correlation data showed that 68% of elevated-defect shifts had a documented conveyor speed variance — but these variances were recorded in the maintenance log, not flagged to quality, and not correlated with defect data

The team validated the predictive relationship for all four leading indicator candidates by analyzing 18 months of historical maintenance logs, solder bath records, and daily defect data. The strongest validated predictors were bath temperature stability (correlation with same-shift solder defect rate: r=0.71) and conveyor speed variance (periods with documented variance showed 2.8× the defect rate of compliant periods).

Causal Chain 2: Component Placement Defects

Component placement defects in SMT were traced to four primary causal conditions:

- Pick-and-place nozzle condition: nozzle wear and contamination were the primary mechanical cause of misplacement — worn nozzles have reduced vacuum reliability and off-center pick tendency. Nozzle inspection frequency and replacement records existed but were not tracked as a quality leading indicator
- Vision system calibration currency: the pick-and-place machines' vision systems required periodic calibration; the team found that 14 of 22 documented misplacement events in the prior year occurred on machines that were overdue for vision calibration
- Feeder maintenance: component feeder tape advancement irregularities were the second-most-cited cause by operators; feeder PM records showed that deferred feeder maintenance correlated with elevated misplacement rates
- First-article inspection completion: the team discovered that first-article inspection (FAI) completion — verifying correct component placement on the first board of each production run — was not consistently completed. Records showed FAI completion at only 73% of production run starts

The most surprising finding from this analysis: the 14 misplacement events correlated with overdue vision calibration represented a pattern that had never been noticed because calibration records and defect records were maintained in separate systems with no integration. Once the data was combined and analyzed, the correlation was immediately visible.

Causal Chain 3: Inspection Detection Failures (Escapes)

The three customer escapes that had triggered the quality crisis were all cases where AEM's inspection process had failed to detect defects that were present — in-circuit test had passed boards that contained failures detectable by the customer's incoming inspection or field test. The escape analysis produced four leading indicator candidates:

- ICT fixture condition: ICT test fixtures use spring-loaded test probes that wear over time. Worn probes produce intermittent contact failures — the defect may or may not be detected on a given test cycle. Probe replacement records were maintained but not correlated with escape events. Analysis of the three escape events showed that all three were tested on fixtures with overdue probe replacement
- Near-miss reporting rate: the team noted that AEM's near-miss reporting system — which allowed operators and inspectors to flag potential quality issues that did not generate a formal nonconformance — had shown declining submission rates over the prior year. The

declining near-miss rate had not triggered any management attention. In retrospect, it preceded the increase in escapes by approximately four months

- AOI correlation to ICT: automated optical inspection should catch defects that would otherwise reach ICT and escape. The team found that AOI 'accept' rate on boards that subsequently failed ICT — a measure of AOI miss rate — had been trending upward without anyone tracking it as a leading indicator of escape risk
- Inspector certification recency: quality technicians performing final manual inspection required periodic re-certification on IPC-A-610 acceptance criteria. Review of certification records showed that 4 of 7 quality technicians on the second shift had certifications more than 18 months old with no refresh

The Leading Indicator Dashboard: What AEM Built

Following the causal chain analysis, Kenji designed AEM's first leading indicator dashboard. The design followed three principles: every leading indicator was validated against historical data before being added; every indicator had a defined threshold with a pre-specified management response; and every leading indicator was paired with the lagging outcome it predicted.

Leading Indicator	Measurement Method	Target / Threshold	Response When Threshold Crossed
Wave solder bath temperature stability (daily Cp measurement)	Automated temperature log; Cp calculated daily from continuous logger data	Cp ≥ 1.33 daily; alert if Cp < 1.20 for any 4-hour production block	Cp < 1.20: production supervisor + quality engineer notified immediately; heating element inspection before next run
Conveyor speed verification compliance	Operator verification at each job changeover; recorded in MES	100% compliance target; alert if any shift < 100%	Any non-compliance: investigate cause before continuing; retrain if procedural; repair if equipment issue
Pick-and-place nozzle inspection currency	Maintenance records; percent of nozzles inspected within 72-hour interval	≥ 95% of nozzles inspected within interval; alert if < 90%	< 90%: maintenance scheduling review; overdue nozzles prioritized same day
Vision system calibration currency	Maintenance records; percent of machines within calibration interval	100% current target; any overdue = immediate flag	Any overdue: machine taken offline for calibration before next production run
FAI completion rate	MES production order records; FAI completion recorded at run start	≥ 98% target; alert if < 95%	< 95%: investigate which runs missed FAI and why; supervisor reinforcement; escalate if systemic
ICT fixture probe	Fixture maintenance records; percent of fixtures	100% current target; any	Any overdue: fixture queued for probe replacement before next

Leading Indicator	Measurement Method	Target / Threshold	Response When Threshold Crossed
replacement currency	with probes replaced within interval	overdue = immediate flag	use; temporary duplicate fixture assigned if available
Near-miss reporting rate (weekly submissions)	Quality system submission log; weekly count per 100 employees	≥ 8 submissions/week baseline; alert if < 5 for two consecutive weeks	< 5 for two weeks: quality director investigation of reporting culture; team leader conversations; systemic barrier identification
AOI miss rate (defects accepted by AOI that fail ICT)	Cross-reference of AOI accept records with ICT failure records; weekly calculation	≤ 0.5% AOI miss rate; alert if > 0.8%	> 0.8%: AOI program review; inspection parameter optimization; potential inspection point addition
Inspector certification recency	Training records system; percent of quality technicians with certification < 12 months old	≥ 95% current (within 12 months); alert if < 90%	< 90%: recertification scheduled within 30 days for those overdue; no solo final inspection for uncertified technicians

The Implementation: 12 Months at AEM

The leading indicator dashboard was fully operational by the end of the second month after the analysis was completed. The following timeline describes the most significant events in the first 12 months of operation:

Month	Event and Outcome
Month 1	Dashboard goes live. Immediate finding: ICT fixture probe replacement for Line 3 wave solder test fixtures is 60 days overdue on two of seven fixtures. Fixtures taken offline for probe replacement before the next production run — which included a medical device customer's boards. An escape that would not have been detected until customer testing is prevented.
Month 2	Near-miss reporting rate is 3 per week — below the 5-per-week alert threshold. Kenji conducts team leader conversations and identifies a specific trigger: two months prior, a near-miss report had been used in a performance conversation with the submitting operator, directly contradicting the program's no-blame intent. The organizational message had been that near-miss reports could be used against you. Kenji addresses this explicitly in a facility-wide communication and reinforces the no-consequences guarantee. Near-miss rate increases to 9 per week within four weeks.
Month 3	Solder bath temperature Cp drops to 1.15 on Line 4's wave solder system — below the 1.20 alert threshold — during the Tuesday night shift. Quality engineer notified at shift start Wednesday. Heating element inspection identifies a failing thermocouple controller. Controller replaced before Wednesday's production run. Line 4's solder joint defect rate that week: 0.8% — below the facility average of 1.2% during a week when the equipment failure would historically have produced a defect rate spike of 2.5–3%.

Month	Event and Outcome
Month 5	AOI miss rate increases to 0.91% — above the 0.80% alert threshold. Investigation reveals that an AOI program update performed during a changeover had inadvertently altered the pad inspection parameters for a high-volume connector component. The parameter error was causing AOI to pass connector placement defects that should have been flagged. Parameter corrected; AOI miss rate returns to 0.3% within one week. Estimated: 18,000 potentially affected boards would have reached ICT and customer test before the error was found via the lagging route.
Month 7	FAI completion rate drops to 89% during a week with three new product launches. Investigation reveals that the FAI procedure requires engineering sign-off before production release, and two of the three product engineers were out on the same week. No back-up approval process existed. FAI back-up authorization procedure created and implemented. FAI completion returns to 98%+ in subsequent weeks.
Month 9	Second-shift inspector certification recency drops to 71% — four of seven second-shift quality technicians have certifications > 18 months old. Recertification training scheduled for all four. During the interim period, second-shift final inspection is supplemented with a 100% AOI review for product families requiring Class III inspection, reducing the risk exposure during the recertification window.
Month 12	Annual review: zero customer escapes in the 12-month period (vs. three in the prior 18 months). Internal defect rate at ICT reduced from 3.4% to 1.7% — 50% reduction. Near-miss reporting rate: 11 per week average in months 10–12. The customer who had placed AEM on formal corrective action removes the corrective action requirement after reviewing AEM's leading indicator dashboard and 12-month outcome data.

Kenji Murakami on the 12-Month Journey

'The most significant moment of the year was the thermocouple finding in Month 3. That single event demonstrated to the entire quality team — and to our leadership — that the leading indicator system was doing exactly what we said it would do. We had a process condition signal, we investigated, we found a real equipment failure, we fixed it before it produced defects. For the first time in my career at AEM, we prevented a quality failure rather than investigating one.'

'The near-miss reporting finding in Month 2 was equally important, but for a different reason. It revealed that the quality culture was the leading indicator that we had been neglecting the most. When people stop reporting near-misses, it means they have stopped believing that the quality system is safe to be honest with. That is the leading indicator of every major quality failure — the system stops getting honest information about what is actually happening.'

'I hear organizations say they cannot measure leading indicators because they do not know which ones to use. The answer is: do the causal chain analysis. Start with your worst lagging outcome. Work backward to the process conditions that produce it. You will find leading indicators in your own operation — often in data systems that already exist but that have never been connected to quality outcomes.'

Metric	Before Leading Indicator Program	12 Months After
Customer escapes	3 in prior 18 months	0 in 12 months
Internal defect rate at ICT	3.4%	1.7% (50% reduction)

Metric	Before Leading Indicator Program	12 Months After
Near-miss report rate	3/week (at start)	11/week average (months 10–12)
ICT fixture probe overdue rate	Not measured	0% overdue — 100% current maintained
Vision system calibration overdue	Not measured; 14 misplacement events traced to overdue machines	0% overdue — 0 misplacement events traced to calibration in 12 months
FAI completion rate	73%	97%
Preventive quality actions generated	Near zero — system was entirely reactive	34 preventive interventions in 12 months; 6 estimated to have prevented customer escapes
Customer corrective action status	Active corrective action requirement from major customer	Corrective action requirement removed at month 12 review

Section 5: Common Mistakes in Leading Indicator Design

Organizations that attempt to add leading indicators to their quality measurement systems encounter a consistent set of design and implementation mistakes. These mistakes do not undermine the concept of leading indicators — they undermine specific implementations of it, often causing organizations to conclude that leading indicators 'don't work' when in fact they had not designed them correctly.

Mistake	What It Looks Like and How to Avoid It
Measuring activity, not process conditions	'Number of quality training sessions conducted' is an activity. 'Percentage of operators with current certification in required skills' is a process condition. Activity metrics document effort; process condition metrics predict outcomes. The test: if the activity happened but the condition did not change, would quality improve? If yes, you are measuring the right thing. If no, you are measuring the effort but not the result of the effort.
Selecting indicators without validating predictive relationships	An indicator that seems logically connected to a quality outcome may not actually predict it in your specific process context. 'PM completion rate seems like it should predict machine defects' is a hypothesis, not a validated leading indicator. Before adding a leading indicator to the dashboard, verify the relationship using historical data or prospective tracking.
No defined threshold or response	A leading indicator without a defined threshold and pre-specified response is just another metric. When PM completion is 87%, what happens? If the answer is 'we discuss it,' the indicator has no preventive function. Every leading indicator must have a threshold (the value at which the predictive relationship suggests risk is elevated) and a defined response (the specific

Mistake	What It Looks Like and How to Avoid It
	action that will be taken when the threshold is crossed), specified before the indicator goes on the dashboard.
Too many leading indicators	A dashboard with 30 leading indicators creates measurement overhead that teams cannot sustainably manage and diffuses management attention across too many signals simultaneously. A well-designed leading indicator system focuses on the 5–10 most predictive indicators for the most consequential quality outcomes. Start with fewer, validate them, and add only when organizational capacity exists to monitor and respond to additional indicators.
Indicators that cannot be acted on before the outcome	If the time lag between the leading indicator and the outcome is shorter than the time required to take corrective action, the indicator does not enable prevention — it only provides a slightly earlier version of the same bad news. Verify that sufficient time exists between the indicator signal and the predicted outcome to complete the required response. If not, look for an earlier point in the causal chain where measurement would provide adequate response time.
Allowing leading indicators to be gamed	Any metric that is measured through self-reporting without verification creates an incentive for the reporting to reflect the desired value rather than the actual condition. Process compliance rates reported by the operators being measured are particularly vulnerable. Design leading indicators that are measured independently — by quality engineers observing the process, by automated systems recording parameter values, by maintenance records audited by quality — rather than self-reported by the process performers.
Not connecting leading indicators to lagging outcomes in reviews	When leading indicators are reviewed in isolation — without connection to the lagging outcomes they predict — the organizational understanding of their predictive value erodes. If your quality review shows PM completion separately from machine defect rate with no explicit connection between them, the team will not develop the understanding that when PM completion drops, machine defects will follow. Always review leading and lagging pairs together, with explicit discussion of the predictive relationship.

The Special Case: Near-Miss Reporting as a Meta-Leading Indicator

Near-miss reporting rate deserves special treatment because it functions as a meta-leading indicator — an indicator of the health of the quality system itself, rather than a predictor of a specific defect type or failure mode. When near-miss reporting is high and increasing, it indicates that the organization's quality intelligence system is functioning: people believe it is safe to surface problems, problems are being detected before they become escapes, and the early warning function of the frontline workforce is active.

When near-miss reporting is low or declining, it indicates one of two things: either there genuinely are very few near-misses (which is a positive signal in a mature, stable process) or people have stopped reporting them (which is a profoundly negative signal). In most manufacturing environments, the latter interpretation is correct — near-miss events are not decreasing; the reporting of them is. This decline in reporting is typically the earliest leading indicator of a developing quality crisis, as Kenji found at AEM in Month 2.

Near-miss reporting rates should always be reviewed in the context of what the organization has done recently in response to near-miss reports. If near-miss reports have generated corrective actions that team members can see and credit — the report was used, something changed — the rate will be sustained or grow. If near-miss reports have generated administrative processing or, worse, negative consequences for the reporter, the rate will decline. The reporting rate is as much an indicator of organizational culture as it is of process health.

Section 6: Building the Organizational Capability

Designing and implementing a leading indicator system is a technical project. Sustaining it as a genuine quality management tool — rather than allowing it to become another compliance checklist — requires organizational capability development that goes beyond the measurement architecture itself.

Teaching Leaders to Use Leading Indicators Effectively

The most common failure mode in leading indicator implementation is not technical — it is behavioral. Leaders who have spent their careers reviewing lagging indicators and responding to quality outcomes often do not know how to respond to a process condition signal that says 'something bad is about to happen.' The response to a defect spike is familiar: investigate, assign a corrective action, track to closure. The response to a leading indicator signal is less familiar: investigate the current process condition, take a preventive action before the defect occurs, and verify that the preventive action restored the indicator to an acceptable range.

This different response pattern must be explicitly taught and practiced. The most effective development approach is to walk through historical events — cases where the data that would have generated a leading indicator signal existed but was not being monitored as a leading indicator — and practice the response that the leading indicator would have enabled. 'If we had been monitoring ICT fixture probe replacement currency and it had triggered an alert three weeks before the escape, what would we have done? Let's walk through that response protocol now.'

Integrating Leading Indicators into Daily Management

Leading indicators only prevent quality failures if they are reviewed frequently enough that threshold crossings generate responses before the predicted outcome occurs. For short-lag leading indicators (process parameters, SPC signals), this requires real-time or shift-level monitoring. For medium-lag indicators (PM completion, calibration currency), weekly review is typically appropriate. For long-lag indicators (near-miss rate trends, supplier quality trends), monthly review may be adequate.

The most reliable integration mechanism is the daily production meeting or shift startup review — a brief, standing meeting where team leaders review the current status of all short-lag leading indicators before production begins. A structured five-minute review of process parameter status, PM completion currency, calibration status, and any open SPC signals from the previous shift ensures that known risk conditions are identified and addressed before they produce defects.

Updating the Indicator Set Over Time

A leading indicator system is not static. As processes change, as new defect modes emerge, and as the validated predictive relationships are confirmed or revised by operational experience, the indicator set must evolve. This requires a formal review cycle — typically annual — in which each leading indicator is assessed against three questions:

1. Is this indicator still predicting the intended outcome? Has the relationship been confirmed by the past year's experience, or have there been cases where the indicator did not signal before an outcome occurred?
2. Are there new quality risks that our current leading indicators do not cover? Are there failure modes we are managing reactively that a new leading indicator could move to proactive?
3. Are any current indicators no longer actionable? Have process changes altered the time lag, or changed the response options, in ways that make the indicator less useful for prevention?

Quick Reference: Leading and Lagging Quality Indicators

Manufacturing Leading Indicator Library

The following leading indicators have validated or commonly accepted predictive relationships with the specified quality outcomes in manufacturing environments. Each should be validated against your specific process data before formal adoption.

Leading Indicator	Predicts (Lagging Outcome)	Measurement Method	Typical Threshold / Alert Condition
PM completion rate	Machine-caused defect rate	% of PMs completed within scheduled window	Alert: < 90% monthly; Critical: < 80%
Equipment calibration currency	Measurement error rate; quality escapes from mis-measurement	% of gages/equipment within calibration interval	Alert: any overdue; Critical: > 5% overdue
SPC out-of-control signal rate	Specification non-conformance rate; customer escape rate	Out-of-control signals per 100 subgroups (per machine, per week)	Alert: upward trend over 2 weeks; Critical: > X signals/week (process-specific)
Process parameter compliance rate	Process-caused defect rate by defect type	% of production cycles with all critical parameters within defined windows	Alert: < 95%; Critical: < 90%
Operator certification currency	Skill-related error rate; procedure deviation rate	% of operators with current certification for their assigned operations	Alert: < 95%; Critical: < 90%
Standard work adherence rate	Process-related defect rate; first-pass yield	% of observed work cycles following documented standard (Gemba walk observation)	Alert: < 90%; Critical: < 80%
Near-miss reporting rate	Quality escape rate; meta-indicator of quality system health	Near-miss submissions per 100 employees per week	Alert: declining trend over 2 consecutive weeks; Critical: > 40% below baseline
Supplier incoming inspection rejection rate	Production yield on runs using that supplier's material	% of incoming lots rejected or placed on hold by supplier	Alert: any new supplier rejection; Critical: > 2 rejections in rolling 90-day window

Leading Indicator	Predicts (Lagging Outcome)	Measurement Method	Typical Threshold / Alert Condition
Tooling wear rate vs. replacement schedule	Dimensional drift defect rate; tooling-caused scrap	% of cutting/forming tools within scheduled replacement interval	Alert: any tool at > 90% of replacement interval without inspection; replace before threshold
First-article inspection completion rate	Setup-related defect rate; first-run defect spike	% of production run starts with FAI completed before full run approval	Alert: < 98%; Critical: < 95%

Leading Indicator Design Checklist

Use this checklist before adding any new leading indicator to the quality dashboard:

	Design Requirement
☐	The indicator measures a process condition or input, not an activity or a result
☐	The specific lagging outcome this indicator is intended to predict has been identified
☐	A plausible causal mechanism connecting this indicator to the outcome has been articulated
☐	The predictive relationship has been validated using historical data or prospective tracking
☐	The time lag between indicator change and outcome change has been estimated and documented
☐	A threshold value has been defined — the level at which the indicator signals elevated risk
☐	A specific management response has been pre-specified for when the threshold is crossed
☐	The measurement method produces objective data, not self-reported compliance
☐	Sufficient time exists between the indicator signal and the predicted outcome to complete the pre-specified response
☐	The indicator is paired with its predicted lagging outcome in all review formats
☐	A review frequency has been defined that matches the time lag of the predictive relationship
☐	An annual review cycle has been scheduled to validate that the predictive relationship remains active

Balanced Scorecard Template: Leading and Lagging Pairs

Quality Domain	Lagging Indicator	Leading Indicator(s)
Process Quality	Internal defect rate; first-pass yield; scrap and rework cost	Process parameter compliance rate; SPC signal rate; standard work adherence rate; first-article inspection completion
Equipment Reliability	Machine-caused defect rate; unplanned downtime; OEE	PM completion rate; equipment calibration currency; tooling wear vs. replacement schedule; bearing/wear-part inspection currency
Human Performance	Operator-caused defect rate; procedure deviation rate; human error count	Operator certification currency; standard work adherence rate (observed); near-miss reporting rate
Incoming Material	Material-caused defect rate; incoming inspection rejection rate	Supplier incoming rejection rate; material property trend vs. specification limits; supplier quality scorecard trend; lot traceability compliance rate
Inspection Effectiveness	Customer escape rate; customer complaint rate; field return rate	ICT/AOI fixture maintenance currency; inspector certification recency; detection coverage audit score; near-miss report rate
System Health	Audit findings (internal/external); CAPA cycle time; regulatory findings	Near-miss reporting rate; preventive action rate vs. corrective action rate; CAPA effectiveness rate; audit finding recurrence rate

Key Terms — Glossary

Term	Definition
Lagging Indicator	A quality metric that measures outcomes — results of processes that have already completed. Tells you what has happened. Examples: defect rate, customer complaint rate, warranty claims. Essential for accountability and trend tracking; structurally limited to reactive management.
Leading Indicator	A quality metric that measures process inputs, conditions, or behaviors that precede and predict quality outcomes. Tells you what is likely to happen. Must have a validated predictive relationship with a specific quality outcome to be genuinely useful. Enables proactive, preventive quality management.
Predictive Relationship	The demonstrated statistical and/or causal connection between a leading indicator and the quality outcome it is intended to predict. A leading indicator without a validated predictive relationship is an unvalidated hypothesis, not a management tool.
Time Lag	The typical delay between a change in a leading indicator and the corresponding change in the predicted quality outcome. Essential for

Term	Definition
	designing monitoring frequency and response protocols — the time lag determines how much advance warning the indicator provides.
Causal Chain Analysis	The method of working backward from a specific quality outcome through each contributing causal step until measurable upstream inputs are identified. The primary method for identifying valid leading indicator candidates.
Threshold	The value of a leading indicator at which the predictive relationship suggests that quality risk has become elevated and management action is warranted. Must be defined before the indicator is deployed, not at the review meeting when the threshold is first crossed.
Near-Miss Report	A report of a quality-relevant condition, event, or observation that did not produce a defect or escape but had the potential to do so. Near-miss reporting rate is a meta-leading indicator of quality system health — reflecting both the actual frequency of risk events and the organizational culture's willingness to surface them.
Preventive Action	An action taken in response to a leading indicator signal before the predicted quality outcome occurs. Distinguished from a corrective action, which is taken after a quality outcome has occurred. The operational goal of leading indicator monitoring.
Process Capability (Cpk)	A statistical measure of how well a process meets specification requirements, accounting for both spread and centering. Used as a leading indicator when tracked over time — declining Cpk predicts increasing specification non-conformance rates before the non-conformances are numerous enough to show in defect rate data.
SPC (Statistical Process Control)	The use of control charts to monitor process outputs over time. SPC out-of-control signals function as real-time leading indicators — they signal that the process has changed in a way that predicts increased specification non-conformance, while the product may still be within specification at the time of the signal.
Measurement System Validity	For leading indicators, the requirement that the measurement method produces objective, verifiable data rather than self-reported compliance. Invalid measurement systems allow leading indicators to be gamed — reporting the desired value rather than the actual process condition.
Balanced Quality Scorecard	A quality measurement architecture that pairs each important lagging indicator with at least one validated leading indicator, ensuring that every outcome measurement has a corresponding process condition measurement that provides advance warning.

Final Thoughts — The Measurement System That Prevents

The first preventive action at Ardmore Electronics — identifying overdue ICT fixture probes in Month 1 before they produced a customer escape on a medical device customer's boards — was worth more than twelve months of post-escape corrective actions would have been. Not just in direct cost avoided, but in the nature of the quality event itself: a known risk condition, addressed before it became a customer failure, instead of an unknown quality failure that reached a customer and required investigation, notification, and corrective action after the harm was done.

This is the fundamental value proposition of leading quality indicators, stated simply: the quality failures you prevent through process condition monitoring do not need to be investigated, reported, corrected, communicated to customers, or defended in audits. They do not appear in lagging indicator dashboards because they did not happen. The prevention is invisible — which is precisely why organizations that measure only lagging indicators do not know what they are not preventing.

Every quality management system that is primarily lagging-indicator-based is spending the majority of its energy investigating, explaining, and correcting quality failures that a well-designed leading indicator system could have prevented. This is not a criticism of the people running those systems — it is a description of what lagging-only measurement is structurally capable of doing. Lagging indicators cannot prevent; they can only inform. Prevention requires knowing what is about to happen, which requires measuring the conditions that produce outcomes before those outcomes occur.

Building a balanced measurement system takes time — the causal chain analysis, the historical data review, the indicator validation, the threshold design, the response protocol development. It is more demanding than adding a column to an existing quality dashboard. But the return on that investment, measured in quality failures prevented rather than quality failures responded to, is the difference between a quality management system that manages problems and one that prevents them. The most important quality metric of all is the one you never have to report because the failure never occurred.

The Four Principles of Leading Indicator Quality Systems

1. Pair every lagging outcome with a leading predictor — for every quality outcome you measure, identify and validate at least one process condition that predicts it before it occurs.

2. Validate before deploying — a leading indicator without a confirmed predictive relationship is an unvalidated hypothesis that creates measurement overhead without prevention value. Do the analysis before adding the indicator.

3. Pre-specify the response — every leading indicator threshold that is crossed must trigger a defined response, decided in advance. A leading indicator that generates discussion but no action has no preventive function.

4. Near-miss rate is the system's vital sign — the rate at which the organization reports near-misses and potential quality conditions reflects both process health and cultural health. A declining near-miss rate is the earliest leading indicator of a quality system losing its ability to see itself clearly.

Sources & Further Reading

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