ProcessRoute
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Is it Clean?!

Why “clean” is never absolute — and how to define “clean enough” for your process

Technical whitepaper

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Abstract

“Clean” is one of the most misused words in high-tech manufacturing. A wafer, surface, component, chemical, or tool is not “clean” in a universal sense — it is only clean relative to a defined purpose, a risk model, and a measurement method. This paper introduces a practical framework to define clean enough, align engineering and management expectations, and reduce misunderstandings between suppliers, fabs, and internal stakeholders.

0) Is it clean? A simple example

Think about everyday life: after dinner, dishes are dirty. We put them into the dishwasher, run a cleaning cycle, and we say the dishes are “clean”. For the purpose of eating from them, that is true. But are they “clean enough” for an operating room? Probably not — especially not after handling them with bare hands and putting them back into storage. And even when dishes look clean to the naked eye, a simple light microscope would likely reveal contamination and defects on the surface.

This small example contains the full lesson: “clean” only makes sense when we define the use case, the measurement method, and the point in time. Clean is always relative, never absolute.

1) The misunderstanding: “clean” as a universal truth

In engineering discussions, we often treat “clean” like an absolute statement: “The wafer is clean.” “The bath is clean.” “The tool is clean.” This language creates friction: false confidence (“clean means safe”), escalation loops (“still not clean enough”), and supplier/customer conversations where both sides think they agree but actually mean different things.

A cleanliness statement should therefore always answer three questions: clean for what, clean from what, and clean when.

Key rule: Clean is not a property. Clean is a specification outcome.

1.1 Cleaning is not deterministic

A second misunderstanding is the belief that the result of a cleaning process is defined only by the cleaning recipe itself. In reality, cleaning success depends strongly on the incoming state of the object: the contamination type, how strongly it is bound, and whether a viable removal approach exists within the constraints imposed by the production flow.

Upstream steps define what must be cleaned — and they also influence whether cleaning will be easy or difficult, cheap or expensive. Downstream steps decide whether the achieved cleanliness is preserved or compromised again. Fresh dishes cleaned immediately are likely clean after the cycle. Dishes left for a week or exposed to high temperature may keep baked-in residues, even when the cleaning process ran perfectly to specification.

The same is true in high-tech manufacturing: identical cleaning recipes can produce different outcomes when the incoming contamination state differs. Some “contamination” (for example embedded particles or subsurface defects) may not be realistically addressable by cleaning and should be treated as a material or process defect rather than a cleaning failure.

1.2 The cleaning tool must be clean

A cleaning tool is not a neutral machine. It is part of the contamination system and can become a contamination source itself. Teams often define the cleanliness requirements of the product, but do not define the hygiene requirements of the cleaning tool.

A cleaning result is influenced by the entire cleaning system: tool-internal surfaces, media supply, chemistry, rinse water, gases, filters, nozzles, seals, moving parts, wear sources, carriers, and the cross-contamination history of previous lots. If the tool background is not controlled, even a well-designed recipe can produce unstable or misleading results.

A practical rule is: you cannot consistently clean a product “better” than the contamination background of the system that processes it. Tool hygiene must therefore be measurable, trendable, maintained, and owned — otherwise it remains an assumption instead of a controlled variable.

Finally, a cleaning tool does not stay clean by default. Residues accumulate, filters load, components age, seals and moving parts wear, and internal surfaces can change their contamination release behavior. Scheduled cleaning, qualification checks, and preventive maintenance are part of keeping the tool a cleaning tool.

1.3 Cleaning is a chain, not an island

Even a strong cleaning step can be defeated by what happens before and after it. Cleanliness is not created by a single recipe alone; it is the result of a chain of process steps, handling actions, transport conditions, storage time, and environmental exposure.

In practice, the relevant question is rarely “Was it clean directly after cleaning?” but rather: Is it still clean enough at the moment it is used?

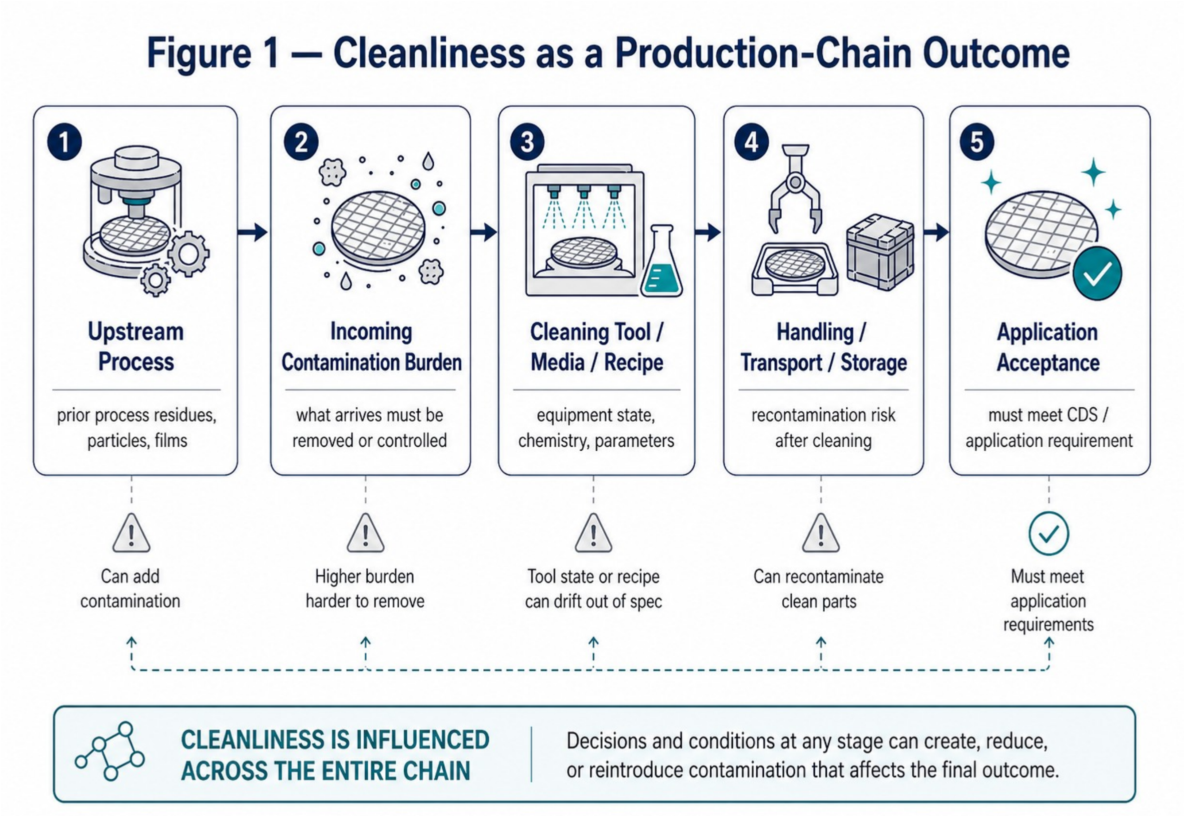

Figure 1. Cleanliness is not created by a single cleaning recipe alone. It is the result of the full production chain: upstream contamination burden, cleaning system condition, handling, storage, and application-specific acceptance requirements.

2) There are different kinds of “dirty”

The question “Is it clean?” is incomplete. The real question is: clean with respect to what failure mode? Contamination is not one thing. In semiconductor and high-tech processing, “dirty” may mean particles, organic films, inorganic residues, metallic contamination, ionic residues, surface chemistry changes, native oxide growth, watermarks, or micro-topography changes. Different failure modes require different definitions of “clean enough”.

2.1 A special case: electrostatic charge (ESD risk)

Electrostatic effects are not classical contamination, but they are often part of the same fit-for-purpose cleanliness risk picture. Charge can directly damage sensitive electronics (ESD events) and can also indirectly worsen particle contamination by attracting and retaining particles during handling. Where relevant, ESD/charge control should be captured in the CDS; common reference frameworks include IEC 61000-4-2 and IEC 61340-5-1, and STMicroelectronics provides an accessible overview of ESD protection framing.

3) “Cleanroom clean” is not “surface clean”

A common trap is equating cleanroom classification with surface cleanliness. Cleanroom standards primarily describe airborne particle concentration. They help, but they do not automatically guarantee low ionic contamination, low metal adsorption risk, low residue level, or stable surface chemistry.

It is also important to remember that “cleanroom” is not a universal concept. Requirements vary drastically across industries. Semiconductor cleanrooms can have very different expectations compared with pharmaceutical or medical environments — not only in contamination levels, but also in the types of contamination and failure mechanisms they are designed to control.

Even when stored in excellent cleanroom conditions, surfaces accumulate contamination over time. No surface is “clean forever”. Cleanliness is a state — and that state can drift or degrade.

4) Replace the word with a framework: the Cleanliness Vector

The word “clean” becomes useful when we replace it with a vector:

Cleanliness = What + How much + How measured + Where + When

This framework forces the most important question: clean for what purpose and risk? It also prevents teams from arguing about a word instead of agreeing on a measurable requirement.

4.1 What: define the contamination class

“Dirty” is not one thing. In practice, you must define what kind of contamination matters for your next step and failure mode, for example:

- **Particles** — count and size distribution
- **Metallic contamination / ions** — surface metals, ionic residues, mobile ions
- **Organic films** — photoresist residues, oils, surfactants, hydrocarbons
- **Inorganic residues** — salts, silica, polymer ash, process residues
- **Surface chemistry / oxide state** — adsorption, oxidation, wettability changes
- **Topography / surface damage** — roughness, scratches, deformation, embedded defects

The required definition depends on process sensitivity. “Visually clean” can still be electrically or chemically unsafe.

4.2 How much: define thresholds with units

“Clean enough” requires numerical thresholds. Otherwise, “clean” becomes an endless escalation loop.

Typical ways to express limits include:

- maximum particle count per size class, for example ≥0.2 µm, ≥0.5 µm, or ≥5 µm
- maximum metal surface density, for example atoms/cm^2, or concentration in extracted liquid, for example ppt
- maximum residue thickness, for example nm, or “no visible residue” if the observation method is defined
- maximum ionic load, for example ng/cm^2, ppb, or conductivity, depending on the method

A practical rule: thresholds must be measurable, linked to a failure mode, and realistic for process capability.

4.3 How measured: define method, sampling, and acceptance rule

A cleanliness statement without a measurement method is a trap. A usable definition includes:

- measurement method and tool, including detection limit and repeatability
- sample preparation or extraction approach
- sampling target, sample type, locations, timing, measurement instances, and test frequency
- blanks/background controls
- pass/fail criteria, retest rules, and escalation logic

Example: wafer surface metal contamination can be measured using TXRF, while ultra-trace metals are often captured via VPD + ICP-MS. These methods do not “see” exactly the same thing, so the chosen method becomes part of the definition.

4.4 Where: define the controlled surface or volume

Cleanliness is rarely uniform. A definition must state where it applies:

- blanket vs patterned areas
- center vs edge / bevel / exclusion zone
- contact holes / trenches vs open field
- frontside vs backside
- tool-internal surfaces vs product surface
- liquids, gases, carriers, and cleaning tool background

If the controlled surface or matrix is not defined, results become incomparable and arguments return.

4.5 When: include queue time, handling, storage, and transport

Time is not just a clock. It is everything that happens to the object between “cleaned” and “used”. To make cleanliness stable in the real world, define when it is measured and what events are allowed in between.

Practical time factors include:

- **Queue time** — waiting between steps
- **Idle time** — waiting in a carrier, FOUP, rack, or tool buffer
- **Storage time** — longer-term hold, warehouse, or cleanroom storage
- **Handling** — gloves, contact points, carrier interfaces
- **Transport** — vibration, abrasion, packaging contact, air exchange

Transport must be included explicitly. Moving a “clean” object can introduce defects and recontamination through vibration, packaging contact, air exchange, and handling. Cleanliness must therefore include the condition “clean after transport and handling”, not only “clean after cleaning”.

5) “Clean enough” is always fit-for-purpose

The engineering goal is rarely “perfectly clean” or “as clean as possible”. It is clean enough for the intended function and acceptable risk level. A practical definition is:

Clean enough = the contamination level at which expected failure risk stays below the acceptable threshold for the intended next process step.

The required effort can vary by orders of magnitude. A surface prepared for fundamental material studies under ultrahigh vacuum at 10^{-12} to 10^{-13} mbar follows a very different cleanliness logic than a surface prepared for routine handling, assembly, or a non-critical process step. The point is not to maximize cleanliness effort, but to match the cleanliness level to the use case and risk.

6) The Cleanliness Definition Sheet (CDS)

Most cleanliness conflicts are definition problems. People argue about the word “clean” while implicitly referring to different contamination types, different measurement methods, different timing, and different risk tolerance. The Cleanliness Definition Sheet (CDS) is a one-page contract that converts expectations into enforceable engineering reality.

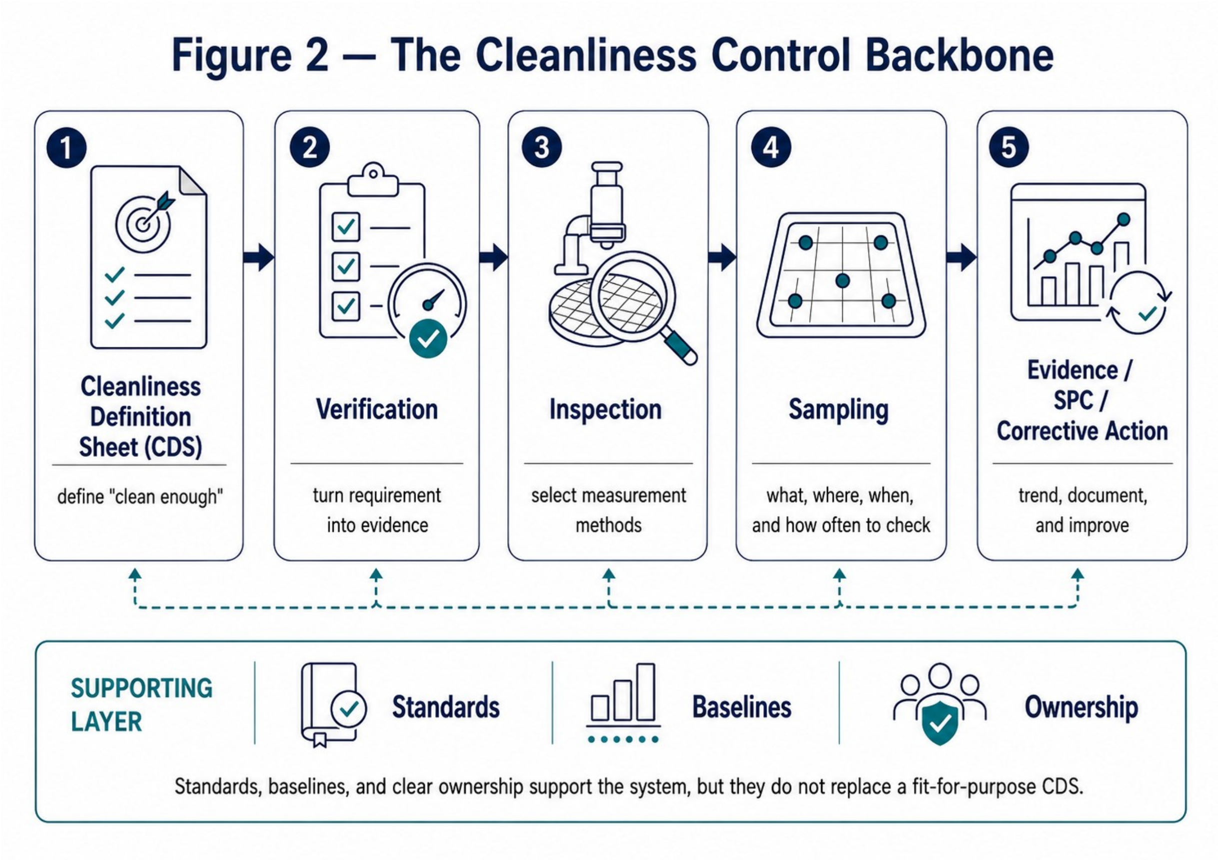

Figure 2. A practical cleanliness program connects definition, verification, inspection, and sampling. Standards, baselines, and clear ownership support the system, but they do not replace a fit-for-purpose CDS.

A CDS should capture, at minimum:

- **Object / scope** — what exactly is being qualified, for example part/wafer, bath, tool module, or carrier.
- **Use case / process step** — where it is used and why it matters; clean is always fit-for-purpose.
- **Stakeholders / owners** — who creates the contamination load upstream, who cleans, who handles/transports, who measures, and who approves/reacts; avoid the trap that “cleaning owns everything”.
- **Failure modes** — what goes wrong if it is not clean enough, for example yield loss, adhesion failure, corrosion, electrical failure, or reliability drift.
- **Contamination types** — what “dirty” means here, for example particles/defects, films/organics, ionic/metal residues, microbial load, or tool background.
- **Limits / thresholds** — numbers, units, and definitions, including pass/fail meaning.
- **Matrix** — where contamination is assessed: surface, liquid, gas, or tool background.
- **Measurement method + capability** — method, limits, repeatability, and for SPC, headroom above detection limits.
- **Sampling plan** — sampling target, sample type, locations, measurement instances per target, timing, test frequency, controls, and evaluation rule.
- **Acceptance rule + escalation** — what happens on deviation, for example retest, quarantine, root cause analysis, maintenance trigger, or supplier action.
- **Verification baseline** — production baseline plus, ideally, a standardized test clean reference.

- **ESD / charge control** — if relevant, because it can drive failures and particle attraction.
- **Applicable standards / reference frameworks** — to support auditability and supplier communication.

From definition to control. A CDS defines what “clean enough” means and how it will be evaluated. Verification turns that definition into evidence that remains valid over time. Inspection provides the method toolbox to detect the relevant contamination classes in the correct matrix. Sampling then makes inspection results meaningful and comparable by defining when, where, and how measurements are taken, under fixed test conditions and with appropriate controls.

In practice, this backbone prevents two common failures: measuring the wrong thing, and measuring the right thing in a way that cannot be trended or trusted.

6.1 Verification: from belief to proving “clean enough”

Cleanliness is not a belief; it is a claim that must be supported by evidence. Verification is the bridge between a written specification (CDS) and stable performance in production. The goal is not to prove “perfect cleanliness”, but to continuously demonstrate clean enough under the constraints of the production flow.

In practice, verification rests on three pillars:

- **Measurement method** — clear procedures, known detection limits, and sufficient headroom for trend monitoring (SPC)
- **Sampling discipline** — defined timing and locations, plus controls, because sampling error can dominate results
- **Stable baselines** — production baselines are useful but can be distorted by upstream variability; standardized test cleans provide a repeatable reference anchor

A standardized test clean is especially valuable because it separates real cleaning-system drift — tool condition, maintenance state, media supply changes — from noise and upstream variability. It makes comparisons across time, tools, and maintenance states meaningful.

In short, verification turns “we cleaned it” into: we can confidently reproduce clean enough.

7) Standards and reference frameworks

Standards are valuable because they create a shared language between stakeholders: engineering, quality, suppliers, and customers. They often define recommended workflows for measurement, documentation, and reporting, and they help avoid inventing everything from scratch. However, standards rarely replace a fit-for-purpose cleanliness definition. Many real processes have unique contamination types, unique surfaces, and practical constraints that standards cannot fully anticipate.

A practical approach is to treat standards as reference frameworks: they support the “how” — typical methods, reporting discipline, auditability — while the CDS defines the “what and how much”: scope, failure modes, contamination classes, limits, sampling, acceptance, and verification baseline.

A key operational benefit of standardized methods and baselines is that they help separate two different questions: did the cleaning system drift, or did the incoming contamination burden change? This separation is one of the core goals of sampling discipline and SPC. Stable test conditions and standardized reference checks make it possible to distinguish “the tool changed” from “the parts changed”, and to react correctly.

8) Measurement reality: no method, no spec

“Clean” is not meaningful without a measurable definition. If you cannot define it precisely, you cannot specify it. If you cannot measure it reliably, you cannot enforce it. If you cannot enforce it, it is not a real requirement — it is only a hope.

In practice, hidden risk enters manufacturing when teams rely on assumptions instead of controlled verification: defined limits, a method with known capability, stable sampling rules, and acceptance criteria.

8.1 Inspection toolbox at a glance

Inspection is not a single activity. It is a toolbox of measurement methods used to detect defined contamination types in a defined matrix: surface, liquid, gas, or tool background. The same contamination class can require different measurement chains depending on the matrix. Therefore, inspection must be defined together with the CDS: what is being detected, why it matters, where it is assessed, and what the production constraints allow.

Three inspection objectives define method requirements:

- Failure discovery maximizes learning and root cause insight. It is acceptable to operate close to method limits and to use slow or complex measurement methods. Manual visual inspection can be highly effective here if a defect is visually detectable.
- Process improvement compares options and quantifies improvement. This requires repeatability and stable baselines, ideally including a standardized test clean reference.
- SPC / stabilization detects drift early and prevents excursions. This requires repeatable measurement methods with headroom above detection limits and a defined calibration/verification routine; otherwise the result becomes an error detector rather than an SPC signal.

A practical rule: SPC needs measurement headroom. If your method operates at its detection or resolution limit, you do not get meaningful control charts — you only get an error detector.

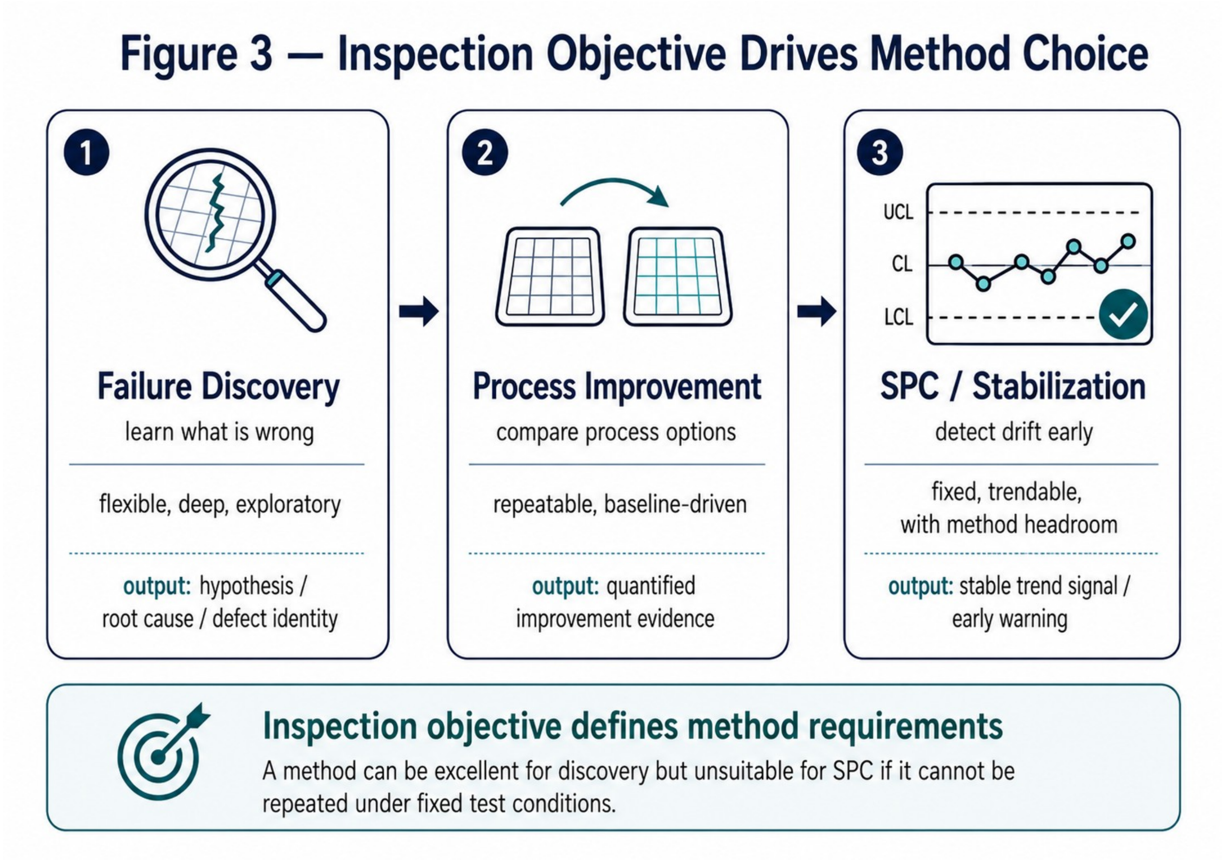

Figure 3. The inspection objective determines the method requirements. Methods that are suitable for failure discovery may be unsuitable for SPC if they cannot be repeated under fixed test conditions or do not provide sufficient method headroom.

Table 1 — Surface inspection toolbox — short-hand view

Tool class	Typical role	Key limitation / warning
Human inspection	Fast triage of visible defects such as scratches, haze, stains, and large particles	Excellent detector, but not repeatable enough for SPC as a measurement
Standardized photography	Tracking visible defects over time	Often needs software and stable lighting to classify and track defects reliably
UV / fluorescence imaging	Fast hunting for organic residues, oils, and some films	Not all residues fluoresce; setup must be stable
Optical scattering scan	Particle-like defect maps on blank/unpatterned substrates	Not usable on patterned or strongly structured surfaces
Optical microscopy	Small particles and local defects	Sensitivity and reproducibility depend strongly on rules and setup discipline
Surface topography metrology	Roughness, scratches, deformation, and step changes	Contact methods can mark sensitive surfaces; area coverage can be limited
Wetting proxy	Fast proxy for organic films or surface-energy changes	Indirect metric; sensitive to roughness, structure, and timing
Surface extraction + chemistry analysis	Quantitative ions, metals, and chemistry residues	Results are dominated by extraction protocol, blanks, and recovery
Deep root-cause tools	Defect morphology and chemistry identification	Too slow or complex for routine SPC

Table 2 — Liquids, gases, and tool hygiene toolbox — short-hand view

Target	Typical role	Key limitation / warning
Liquids: conductivity/resistivity + pH/ORP	Fast health check for basic ionic changes and drift	Not specific; tells that something changed, not what it is
Liquids: particle counter + turbidity	Particle, filter, and bubble-related monitoring	Sampling cleanliness and container protocol dominate reliability
Liquids: TOC	Organic load and bath aging trend	Shows load, not chemical identity
Liquids: IC / ICP	Specific ions and trace metals	Protocols and blanks matter; highly sensitive to sampling contamination
Gases: dew point + particle monitoring	Moisture and airborne particle checks	Sampling position in the flow path matters strongly
Tool background: witnesses / rinse checks / swabs	Tool background release, localized residues, and drift detection	Only meaningful if placement and protocol are standardized

Note: some optical particle/defect scanning approaches require unpatterned or blanket surfaces and are not applicable to structured or patterned surfaces.

8.2 Sampling strategy: seven decisions that make measurements trustworthy

Sampling is not a detail at the end of measurement — it is part of the measurement method. Many cleanliness discussions fail because the sampling error is larger than the instrument error. A good sampling strategy makes results comparable over time and prevents false confidence.

1. Purpose

Start with the decision the data must support: failure discovery, process improvement, or SPC/stabilization. Discovery can be hotspot-biased and exploratory; improvement requires comparability; SPC requires repeatable sampling and method headroom, not operation at the detection limit.

2. Matrix

Define the matrix where contamination lives and will be assessed: surface, liquid, gas, or tool background. The same contamination class can require different measurement chains depending on the matrix. For example, surface ionic contamination often needs extraction before analysis.

3. Sampling target

Define the sampling target: wafer/part, batch, bath, tool run, or shift/day. The sampling target defines what the result statement refers to. Where relevant, define the sample type — how the test sample is generated — for example swab, rinse, witness/coupon, grab sample, or inline reading. Without a clear sampling target, the required measurement instances and test frequency become ambiguous.

4. Timing

Specify the timing of sampling relative to real use: immediately post-clean, after handling/transport, after storage, or at point-of-use. In many applications, “clean right after cleaning” is less relevant than “clean enough at the moment of use”.

5. Locations

Contamination is rarely uniform. Define locations as representative points plus known risk hotspots, for example edges, interfaces, handling points, flow impingement zones, dead volumes, and seals. For SPC, keep the location set stable; for discovery, expand it as needed to find root causes.

6. Measurement instances and test frequency

Choose measurement instances — how many individual measurements per sampling target, such as locations, aliquots, or replicates — and test frequency based on risk, cost, and required confidence. For SPC, it is usually better to measure consistently and trend well than to measure rarely and deeply.

7. Controls and evaluation rule

Controls are non-negotiable: blanks/background checks, consistent handling/containers, and a verification routine. For improvement and SPC, a standardized test clean provides a stable anchor that helps separate cleaning-system drift from upstream variability. Define the evaluation rule — acceptance plus trending — so results are actionable.

Table 3 — Objective vs sampling requirements

Objective	Sampling style	What must be fixed	Typical anchor
Failure discovery	Hotspot-biased and flexible	Enough to learn	Blanks + targeted repeats
Process improvement	Fixed and comparable	Points, timing, and method	Production baseline + standardized test clean
SPC / stabilization	Stable, repeatable, economical	Fixed test conditions	Standardized test clean + calibration/verification

Table 4 — Matrix-specific minimum definitions

Matrix	Minimum to define
Surface	Zones/points, inspected area, timing, handling rules
Liquids	Sampling point in loop, container protocol, flush/discard/stabilization protocol
Gases	Sampling position in flow path, stabilization time/flow, purge/discard/stabilization protocol
Tool background	Witness placement/exposure or rinse protocol, maintenance state, trending frequency

CDS-ready sampling one-liner

“Sample [matrix] on [sampling target] at [locations] with measurement instances = [# per target], at [timing], with test frequency = [interval], using controls [blank + standardized test clean/witness], evaluated by [acceptance + trending rule].”

8.3 Typical failure mechanisms: why “clean enough” is lost

Cleanliness is rarely lost because a single cleaning recipe “did not run”. More often, it is lost because the overall chain introduces variability or recontamination. The most common mechanisms are:

- **Upstream burden** — upstream steps define what must be removed and how difficult removal becomes.
- **Incompatible constraints** — the production flow constrains what cleaning is allowed to do; “more aggressive cleaning” is often not an option.
- **Tool background drift** — residues build up, filters load, components wear, and internal surfaces change over time.
- **Cross-contamination** — lots, carriers, fixtures, and tool history can transfer residues and particles across runs.

- **Post-clean handling and logistics** — handling, packaging, transport, and storage can reintroduce particles, films, or ionic residues.
- **Time-dependent effects** — adsorption, re-adsorption, outgassing, oxidation, corrosion, and moisture effects can change surfaces after cleaning.
- **Electrostatic effects** — charge control failures can cause direct damage and increase particle attraction during handling.
- **Measurement artifacts** — method limits, poor sampling discipline, uncontrolled blanks, or inconsistent extraction protocols can produce false confidence or false alarms.

9) Economics: “cleaner” is not always better

Beyond a certain point, cleaning cost rises steeply while additional risk reduction becomes marginal. In some cases, aggressive cleaning can even create new damage mechanisms, such as roughening, corrosion, adsorption changes, or material compatibility problems. A mature cleanliness strategy is therefore not simply “clean more”. It is: reduce failure risk, avoid unnecessary complexity, and prevent unintended side effects.

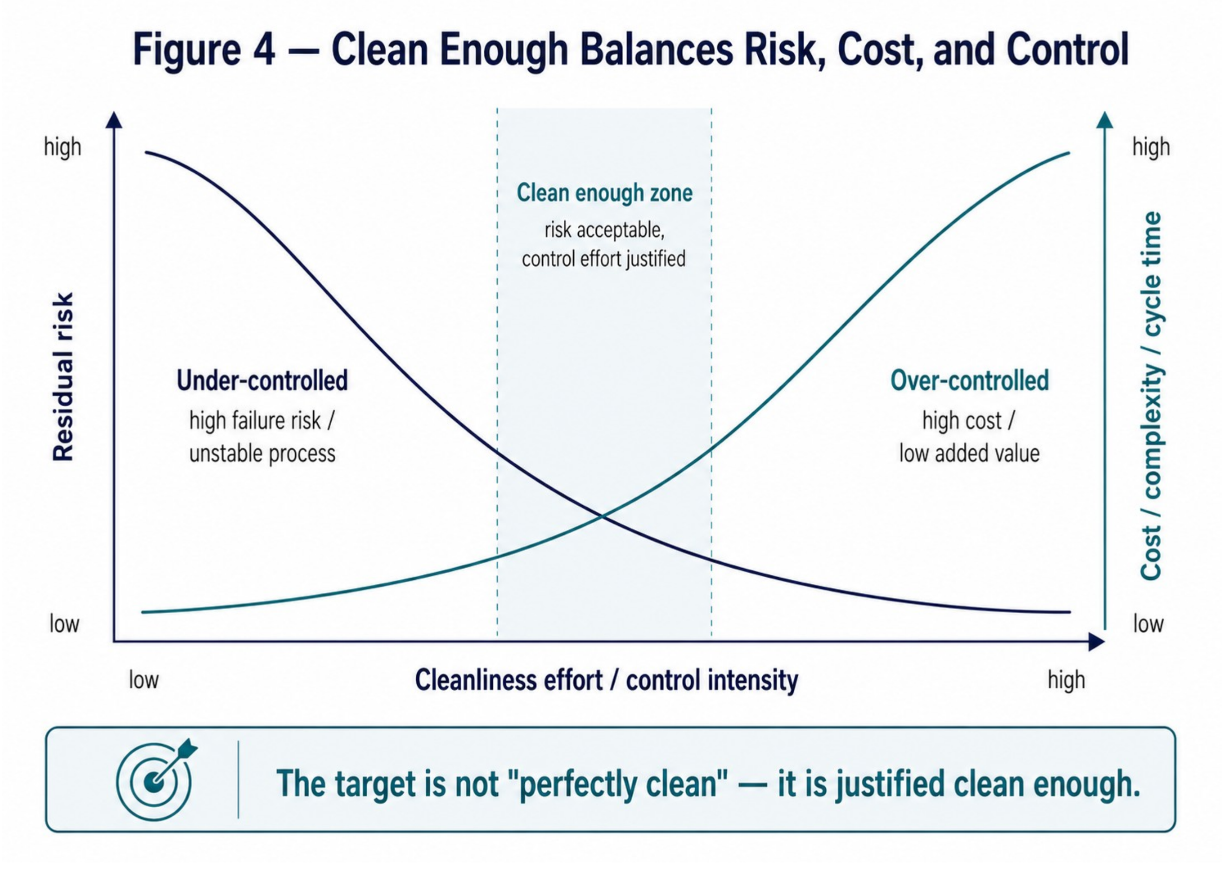
Figure 4 — Clean Enough Balances Risk, Cost, and Control

The target is not "perfectly clean" — it is justified clean enough.

Figure 4. “Clean enough” is a fit-for-purpose balance between residual risk, control effort, and cost. The target is not maximum cleaning effort, but a justified cleanliness level that protects the application without unnecessary complexity.

9.1 LEAN vs CLEAN: the trap

It is sometimes argued that cleaning and cleanliness inspection steps add no value and should be reduced or removed in a LEAN approach. This can be a major trap: it often creates unplanned costs, missed cleanliness specifications, or unstable manufacturing behavior because the object is not within the cleanliness condition required for the next step.

The LEAN solution is not “remove cleaning”. It is: define clean enough, remove over-cleaning beyond that definition, and keep the right inspection at the right point.

10) Checklist for engineers and decision makers

Before saying “it must be clean”, confirm:

- Do we know the failure mode we are preventing?
- Do we know the contamination class that matters?
- Do we have measurable limits and units?
- Do we have a measurement method and known detection limit?
- Is sampling defined: matrix, target, locations, timing, sample type, measurement instances, and test frequency?
- Is the definition stable, or are the goalposts moving?
- Do all stakeholders measure the same thing in the same way?
- **Do we define “clean when”** — after cleaning, storage, transport, handling, or at point-of-use?

Conclusion and key takeaways

Cleanliness is not a single cleaning step. It is a system outcome created — and often compromised — across the full production chain. The practical goal should not be “perfectly clean”, but clean enough, defined for a specific use case and maintained over time.

Key takeaways:

- Define clean enough explicitly. Use a CDS to align scope, stakeholders, failure modes, contamination types, limits, matrix, measurement method, sampling plan, and escalation.
- Verify, do not assume. Verification converts a written definition into evidence. Stable baselines and standardized test cleans are critical to separate cleaning-system drift from changes in incoming contamination burden.
- **Inspection is a toolbox. Select measurement methods based on the inspection objective, the matrix, and production constraints** — not on instrument prestige.
- Sampling makes data meaningful. Define sampling target, sample type, locations, timing, measurement instances, test frequency, controls, and the evaluation rule. Without fixed test conditions, trends are not trustworthy.
- Manage the failure mechanisms. Tool background drift, cross-contamination, post-clean handling/logistics, time-dependent effects, electrostatic risks, and measurement artifacts are common reasons why cleanliness is lost.

Cleanliness succeeds when definition, verification, inspection, and sampling form one consistent backbone — and when ownership is shared across the chain.

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