A Governed Electromagnetic Portioning and Slicing Architecture for Industrial Meat and Fish Processing

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ABSTRACT

Industrial slicers for meat and fish usually run on fixed blade geometry and programmed motion, even though the product changes from piece to piece. Fibre direction, connective tissue, fat, moisture, temperature and bone position all change how a piece responds to a cut. This paper presents PICCOLO, a proposed portioning and slicing architecture that treats each cut as a controlled separation event rather than a forced shear. The machine measures the state of the product and the state of the slicer, and a supervisory control layer uses those measurements to accept, slow, hold, recondition or reject each piece. Five subsystems work together: an electromagnetic (EM) stabilisation ring around the cut zone, predictive feed and indexing control, actuator governance, micro-zonal thermal conditioning, and hygienic surface topology.

The EM ring is not a cutting tool. Its working hypothesis is that a controlled local field can shape the mechanical impedance at the cut zone and reduce cut disturbance. The methodology sets out governing equations, a two-layer control structure, a State-of-Cut observer with 500 to 1,000 Hz sensing and a response target below 20 ms, product-specific starting envelopes for salmon, chicken breast and beef striploin, and a four-phase validation pathway. The results present parameterised analyses of contact stress, vibration and thermal conditioning, with measurable performance definitions, an economic boundary model and five falsifiable predictions, each tied to a pass or fail gate. The paper defines what must be measured to prove or reject each subsystem.

Keywords: Meat and fish processing; Portioning and slicing; Electromagnetic stabilisation; Process control; Hygienic design; Food automation

INTRODUCTION AND LITERATURE REVIEW

The slicing problem

Slicing meat and fish at industrial scale is a geometry problem, a material problem and a hygiene problem at the same time. Meat and fish are not uniform solids. Muscle fibre direction, connective tissue, fat, moisture, temperature history and the position of bones or other inclusions all change how a piece responds when a blade passes through it.

A critical review of cutting in the fish industry identifies cutting, trimming and portioning as central processing steps for yield, and highlights product temperature, automated sensing and product-specific machine setup as controlling factors [1]. Meat protein structure changes with heating history and composition [2], and rheological testing shows that meat behaves as a non-linear viscoelastic material in which elasticity plays a major role [3]. A single fixed machine setting therefore describes only part of the process.

Most current slicers work from fixed blade geometry and programmed motion. Variation between pieces is absorbed by machine tolerance, operator intervention or trimming further down the line. This works well when the product specification is stable. It does not measure the condition of each piece at the moment it is cut. Figure 1 shows the PICCOLO concept proposed in this paper, in a meat-processing configuration.

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Figure 1. PICCOLO governed electromagnetic portioning and slicing architecture shown in a meat-processing configuration, with the EM stabilisation ring, governed feed path, supervisory control interface and controlled-separation output window. The architecture is proposed and requires SKU-specific prototype validation.

Industry context

Investment in cutting equipment is strong. The global meat processing equipment market reached USD 11.8 billion in 2026. Cutting equipment is the largest segment at 28.5% of that market, and the automatic meat portioning machine segment was valued at USD 631 million in 2025, growing at 3.5% a year [4]. Robotic meat processing automation is projected to reach USD 4.5 billion by 2033 at 9.2% a year, driven by labour shortages, yield targets and regulatory compliance [5]. A 2025 review of meat industrialisation reports that intelligent cutting has improved cutting precision to the millimetre level [6]. These figures show sustained capital spending on the class of automated portioning equipment that PICCOLO belongs to.

Automation, sensing and control

Recent reviews define what an automated meat cutter needs. Lyu et al. [7] describe a meat-processing robot as three modules: sensing and perception, control, and actuation. They note that meat is a non-standard flexible material, that its viscoelastic nature places strict demands on force-control accuracy during cutting, and that blood and other fluids make sensor-based recognition harder. André-Zarna et al. [8] review automation in secondary meat processing in the context of Industry 5.0.

They find that automation levels fall as animal size rises, and that the main barriers to adoption are integration cost, strict food-safety compliance and the need for flexible systems that can handle variable raw material. They identify tactile sensing, intelligence, adaptivity and perception as the capabilities current systems lack. Jeong et al. [9] reach a similar view for artificial intelligence: data-driven classification, regression and image analysis are the most mature applications, while physical AI-enabled automation for tasks such as deboning is still at an early stage. For constrained, multi-variable machine control, model predictive control (MPC) is an established method [10], but it needs an identified plant model before it can be applied with confidence.

Upstream bone detection

PICCOLO does not detect bones itself. It relies on upstream imaging. X-ray machine vision for detecting pin bones in salmon and trout fillets has been demonstrated in the peer-reviewed literature for more than a decade [11]. Current commercial inline X-ray systems with AI-guided vision report detection rates above 99.8% at

up to 120 pieces per minute, and robotic cutting systems report portion weights within ±2 g of target [5]. The bone-mapping input that PICCOLO requires is therefore available on the market today.

Electrical properties of meat and fish

Any electromagnetic device near the cut must account for how the product responds to a field. The dielectric properties of foods vary with frequency, temperature, moisture and composition, and they set how much field energy is converted to heat [12]. In pork muscle, dielectric properties change significantly across the temperature range of protein denaturation and differ between meat quality classes [13]. A field state that is safe for one product or temperature may not be safe for another. PICCOLO therefore treats dielectric variability as a measured quantity with its own pass or fail gate.

Hygienic design

Food machinery must be cleanable by design. The European Hygienic Engineering and Design Group (EHEDG) publishes guidelines covering hygienic design, cleanability, sensors, fresh-fish processing and clean-in-place (CIP) installations [14], and 3-A Sanitary Standards set equivalent equipment requirements in North America [15]. Fryer and Asteriadou [16] classify industrial cleaning processes by deposit type and cleaning method, which frames how a cleaning route is matched to a product and its soil.

Prior work and research gap

This paper builds on three earlier food-processing architectures by the author: the High-Integrity Cheese Portioning Architecture [17], the Griffiths Enhanced Double Screw Architecture (GEDSA) [18] and the Griffiths Electromagnetic Bowl Cutter (GEMBC) [19]. Each treats product state, motion, temperature, local field state and hygiene as linked variables rather than separate machine settings. None of them addresses meat and fish slicing, where the product is anisotropic and bone position is a hard limit.

The gap is a slicer that measures the state of the product and the cutter during the cut, acts on that measurement in real time, and states in advance how each of its functions will be proven or rejected. The aim of this paper is to define that architecture, named PICCOLO, and the method for testing it.

The contributions are: (1) a five-subsystem architecture with a two-layer control structure; (2) governing equations that identify what must be measured; (3) an EM stabilisation measurement programme with defined pass and fail criteria; (4) starting envelopes for salmon, chicken breast and beef striploin; and (5) five falsifiable predictions tied to subsystem gates. In this paper, SKU (stock-keeping unit) means one specific product line, such as skin-on salmon fillet.

METHODOLOGY

Research design

This is an architecture-definition study. The method has five steps: (1) define which products the machine may process and the conditions that make a product eligible; (2) define the subsystems and the control structure that links them; (3) write the governing equations that show which variables must be measured; (4) run parameterised analyses that expose the main dependencies before hardware exists; and (5) define the measurement programme, the pass or fail gates and the staged validation pathway that will prove or reject each subsystem. Every acceptance criterion is pre-registered: the product, measurement method, metric and test condition are fixed before results are read.

Product scope and eligibility

PICCOLO is designed for boneless products or products with controlled bone geometry. Controlled bone geometry means one of two things. Either a bone map from qualified upstream imaging (X-ray, CT or another

validated method) is registered to the machine's cut coordinates, or the product is held to a constrained specification by a validated fixture. If neither is available, the product is not eligible for PICCOLO. The machine works alongside existing food-safety controls, inspection, chilling and sanitation programmes and does not replace them. Table 1 sets out how each product variable is handled, and Figure 2 shows the fish-portioning configuration.

Table 1. Product-matrix capability envelope and precondition for operation

Variable	Architecture treatment	Validation boundary
Product temperature	Measured product-state input; micro-zonal conditioning may adjust local state.	Set per SKU through thermal and quality trials.
Fibre and tissue orientation	Product registration and cut-path planning input.	Requires product-specific imaging or fixturing evidence.
Cross-section and thickness	Defines mechanical travel, conditioning reach and actuator constraints.	Maximum geometry set after prototype qualification.
Feed-rate envelope	Governed through path and rate limits.	Bounded by cut quality, stability and safe-stop testing.
Bone or inclusion geometry	Requires a pre-registered upstream bone or inclusion map matched to the cut coordinate system, or a constrained SKU specification held by a validated fixture.	If upstream mapping or a validated constrained specification is unavailable, the SKU is ineligible for PICCOLO use.
Hygiene condition	Product-contact path is designed for washdown and cleanability assessment.	Requires CIP and cleanability validation and applicable certification.



Figure 2. PICCOLO fish-portioning configuration illustrating salmon product flow through the governed cut zone and downstream portion indexing. The image is a conceptual representation.

Each cut is treated as a controlled separation event. The control system receives product and machine signals, applies limits to the cut path, and can accept, slow, hold, recondition or reject a piece when it falls outside its approved operating window (Figure 3). This is a control architecture. The electromagnetic field does not slice the food.

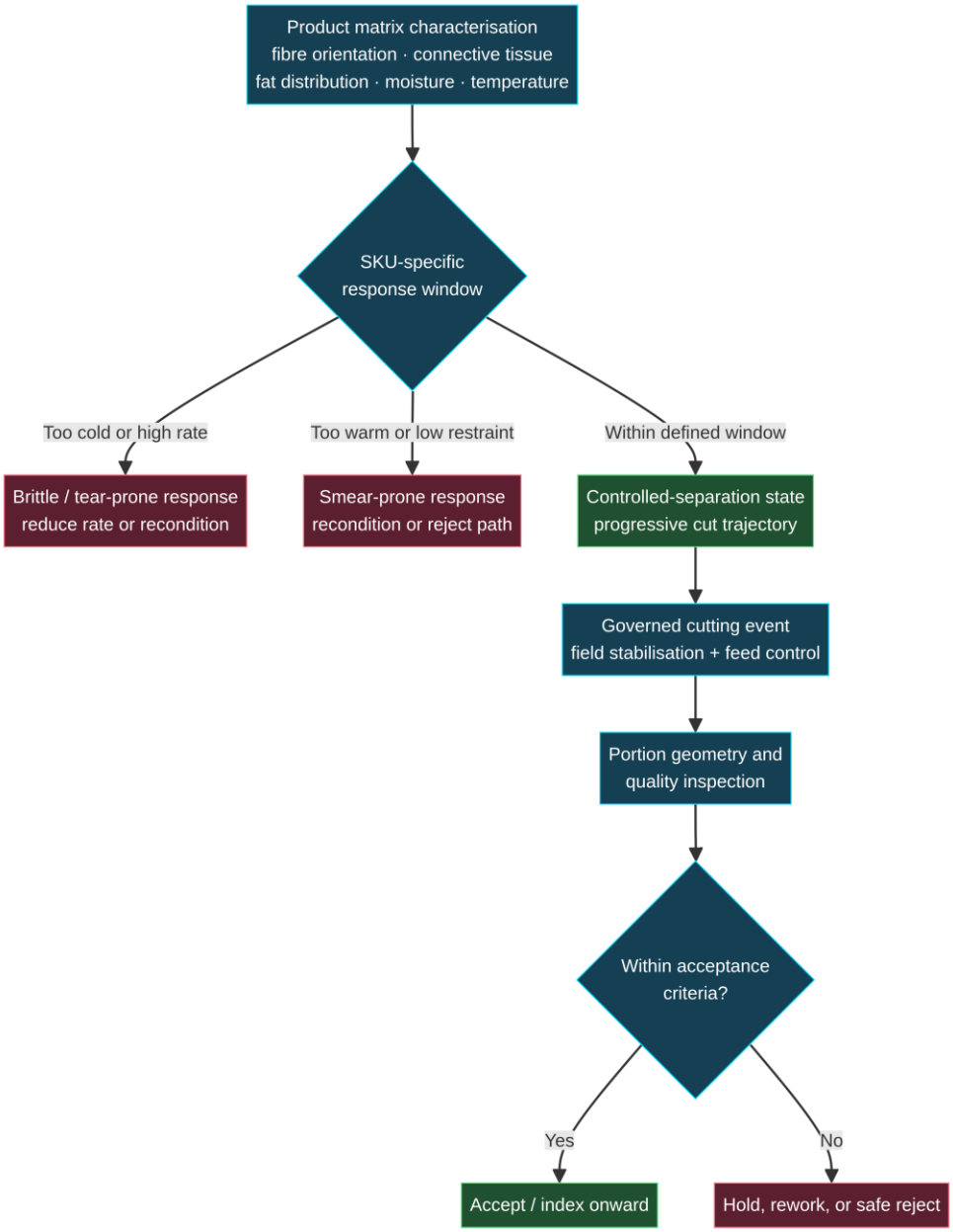

Figure 3. PICCOLO material-state and controlled-separation decision path. The operating window and all acceptance criteria are SKU-specific and are set during prototype validation.

SKU starting envelopes

The first prototype does not run from a generic meat-and-fish setting. Three starting envelopes are defined for salmon, chicken breast and beef striploin (Table 2, Figure 4). Each envelope gives a starting temperature band, a starting feed-rate band and the main properties to check.

The envelopes structure the bench and pilot trials. Each one is set, narrowed, widened or rejected on the basis of mechanical, thermal, hygiene and quality evidence for that product. The stated temperatures sit within the host plant's established cold-chain and food-safety controls.

Table 2. Representative SKU starting envelopes for PICCOLO trial design

SKU	Starting temperature band	Starting feed-rate band	Primary validation emphasis
Salmon	0–3 °C	25–55 mm/s	Fibre and gapping response, local temperature, surface integrity.
Chicken breast	0–4 °C	30–60 mm/s	Moisture response, compression, geometry retention.
Beef striploin	0–5 °C	20–50 mm/s	Fibre direction, connective tissue, trim-path stability.

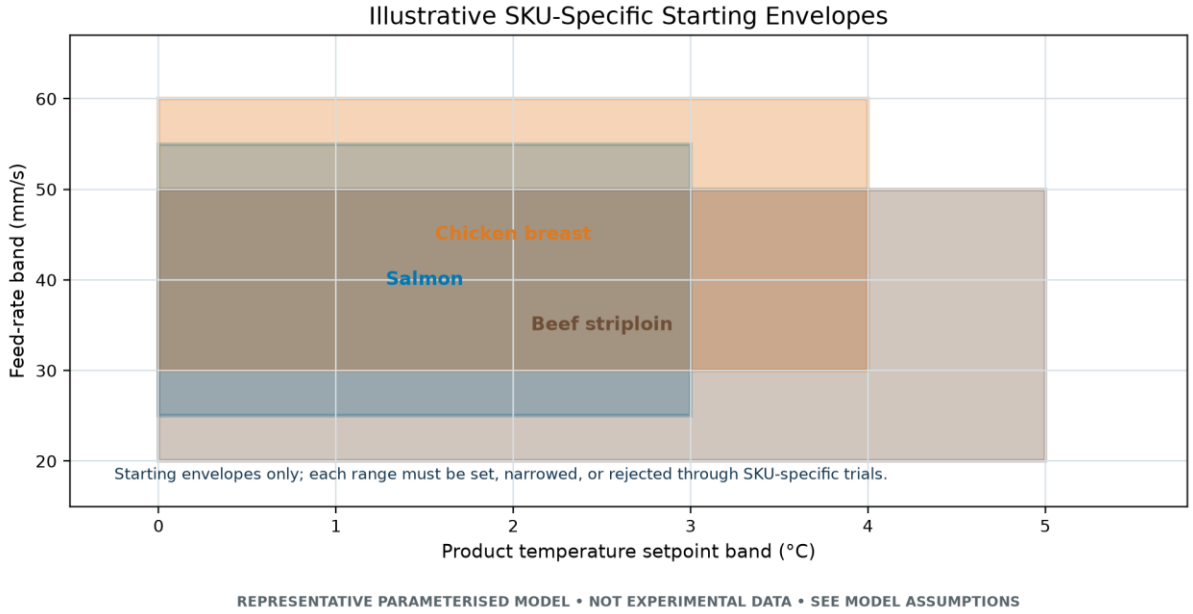

Figure 4. Illustrative SKU starting envelopes for salmon, chicken breast and beef striploin. These are parameterised trial ranges, not validated production settings.

System architecture

PICCOLO has five subsystems that work together under one control layer (Figure 5, Table 3).

EM stabilisation ring. A coil ring around the cut zone creates a controlled local electromagnetic field. Ring current, geometry, frequency content, duty cycle and placement are set only after product-coupling and electromagnetic compatibility (EMC) tests. The ring is not a cutting source, a sterilisation device or a substitute for the blade.

Predictive feed and indexing control. Force, position and torque feedback set the speed and path of the product through the cut. The controller exposes its limits, records the chosen path and enters a hold or reject state when feedback leaves the approved envelope.

Actuator governance. Motion, rate limits and safe stop states are coordinated across all drives.

Micro-zonal thermal conditioning. The surface and near-surface of the product are brought to a product-specific state just before the cut. In Phases 1 and 2 this takes place in a pre-cut dwell zone with controlled residence time. Continuous inline conditioning is a Phase 3 to 4 option, pursued only if footprint, throughput, temperature-gradient and hygiene limits allow. The conditioning method, sensing method, penetration depth and hold time are open engineering variables.

Hygienic surface topology. Product guides, seals, sensors, cut-zone supports, drains and access points are designed together so that no inaccessible residue traps exist. Cleanability governs the layout, not packaging convenience or component density.

Damping, passive isolation, compliant support, structural stiffness and actuator rate limits are not a sixth subsystem. They are shared mechanical support functions that serve all five. The design aim is a repeatable, bounded level of cut-zone disturbance tied to a registered acceptance criterion, not zero vibration.

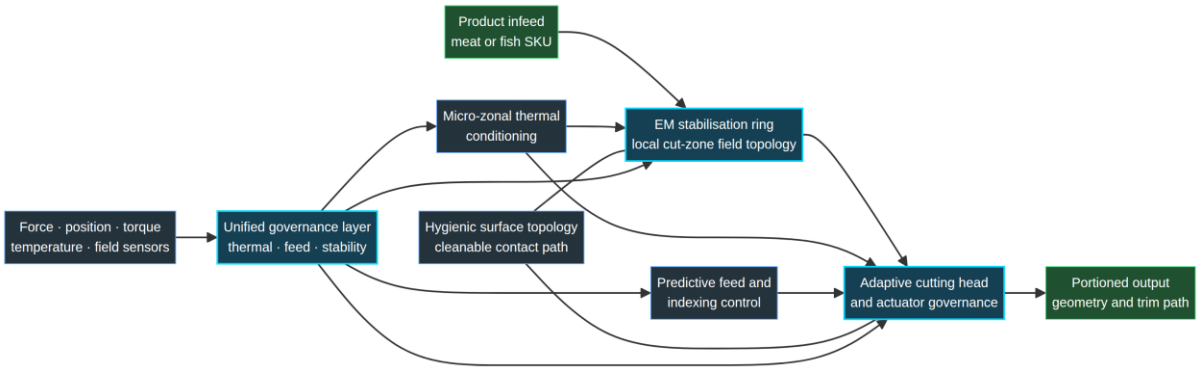

Figure 5. PICCOLO system-level architecture showing product flow, the five coordinated subsystems, shared mechanical support, sensor inputs and the unified control (governance) layer.

Table 3. PICCOLO subsystems, design purpose and verification objective

Subsystem	Design purpose	Primary verification objective
EM stabilisation ring	Establish a measured, governed local field state at the cut zone.	Field mapping, repeatability, EMC, thermal coupling and safe-state behaviour.
Predictive feed and indexing	Constrain the product and tool path against feedback.	Path repeatability, control stability and hold or reject response.
Actuator governance	Coordinate motion, rate limits and safe states.	Mechanical repeatability, vibration response and fault handling.
Micro-zonal thermal conditioning	Bring approved products into a defined response window.	Thermal uniformity, SKU-specific quality response and food-safety review.
Hygienic surface topology	Maintain a cleanable, accessible product-contact path.	CIP and cleanability evidence, drainage, inspection access and materials review.

Hygiene is a design constraint from the start. The concept-stage commitments are accessible contact zones, radius-constrained transitions, drainable geometry, washdown-rated components where required, and a documented verification route against EHEDG and 3-A requirements [14, 15] (Table 4). Washdown conditions are designed in at the actuator and sensor boundary, not retrofitted. Any coating, polymer or electromagnetic-window material needs its own food-contact, fatigue and cleaning validation before it enters a production claim.

Table 4. Hygienic design and cleanability verification plan

Design principle	Concept implementation	Required evidence
Accessible product-contact path	Tool-less or documented-access inspection zones.	Inspection and sanitation procedure trial.
Drainable geometry	Directed flow paths and no unverified pooling zones.	Drainage observation and residue challenge.
Radius-constrained transitions	Avoid abrupt, inaccessible product traps.	Dimensional inspection and hygienic-design review.
Washdown-compatible hardware	Specified seals, sensors, cables and enclosures.	Ingress, corrosion and duty-cycle testing.
CIP and cleaning validation	Documented cleaning route appropriate to the application.	Application-specific cleanability and microbiological evidence.

Control structure

The control system has two layers. The supervisory (governance) layer sets the approved SKU envelope, the accept, hold and reject rules, the safe-state rules and the subsystem gates. It runs at a supervisory rate suited to state estimation and gate decisions. The real-time control layer executes the cut path and closes the force, position, vibration, thermal and field loops at millisecond rates, inside the limits set by the supervisory layer. When limits conflict, a fixed order of priority applies: safety, then hygiene, then mechanical stability, then thermal state, then EM state.

Three loops are coupled. The thermal loop informs the feed loop, because the product's response depends on its local temperature. The feed loop informs the field and stability loop, because a change in path can change vibration at the cut. The field and stability loop informs the feed loop, because measured disturbance must shape the next motion command. A safety envelope sits outside all three loops and can force a safe hold or stop (Figure 6).

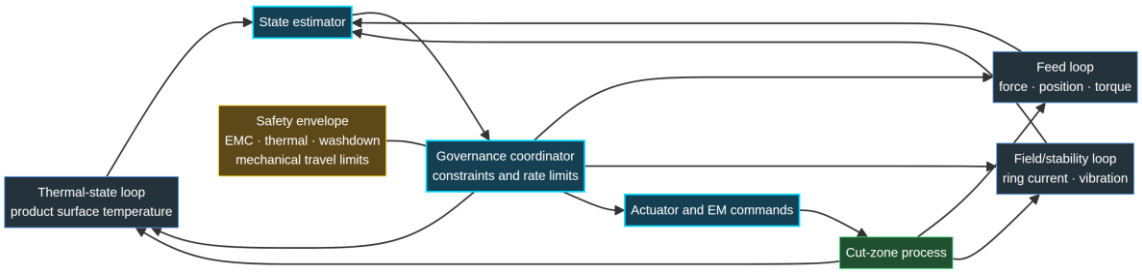

Figure 6. Coupled thermal, feed, EM-stabilisation, State-of-Cut observer and mechanical-support information loops. The safety envelope overrides all loops; supervisory governance sets limits; real-time control resolves conflicts in the order safety, hygiene, mechanical stability, thermal, EM.

A State-of-Cut observer estimates the quality of the separation front during the cut. It is a soft sensor that combines force F, torque τ, vibration v, path state q and the registered SKU state:

$$\hat{y}_{cut} = h(F, \tau, v, q, SKU) \quad (1)$$

Once validated, the observer lets the controller adjust the path, feed rate, hold state or reject routing during the cut, rather than relying on inspection afterwards. Its Phase 1 job is to show that a repeatable estimate can be built and checked against registered reference observations. The timing targets are 500 to 1,000 Hz sampling for force, torque and vibration (1 to 2 ms per sample) and an end-to-end path from sensor to back-off command below 20 ms, with 5 to 10 ms as the design objective. Phase 1 uses PID control with SKU-specific gain scheduling. MPC [10] becomes a Phase 2 to 3 upgrade once plant identification, observer performance and timing budgets are proven.

Governing equations

The equations below show which variables depend on which. They are governing forms, not calibrated plant models. The regulated state and the command vector are:

$$x = [T, F, q, a, I, v]^T, \quad u = [u_{EM}, u_{feed}, u_{act}, u_{thermal}]^T \quad (2)$$

where T is product temperature, F is cut-zone force, q is position, a is actuator state, I is ring current or a field-state proxy and v is vibration. The command u is limited by product, hygiene, EMC, temperature and mechanical-travel limits. At the contact interface, the normal-stress proxy and the effective strain-rate proxy are:

$$\sigma_n = F_n / A_{eff}, \quad \dot{\varepsilon} = v_f / h_{eff} \quad (3)$$

where F_n is normal load, A_{eff} is effective contact area, v_f is feed velocity and h_{eff} is an effective deformation length. These show how load spreading and feed rate interact. They predict tearing or cut quality only after calibration for a specific product. The machine state evolves as:

$$x_{k+1} = f(x_k, u_k, d_k) \quad (4)$$

where d is the product and disturbance input. A constrained predictive controller selects:

$$u^* = \arg\min \Sigma (||x - x_{ref}||^2_Q + ||\Delta u||^2_R) \quad (5)$$

subject to safety, hygiene, field, thermal and travel limits. Structural vibration is represented by a single-degree-of-freedom model, and thermal conditioning by the heat equation:

$$m \ddot{q} + c \dot{q} + k q = F_0 \sin(\omega t) \quad (6)$$

$$\rho c_p \partial T/\partial t = k \nabla^2 T + \dot{q} \quad (7)$$

where k is structural stiffness in Equation 6 and thermal conductivity in Equation 7, and $\dot{q}$ in Equation 7 is the volumetric heat input. The ring field state and its control error are:

$$B_c = f(I, \omega, g, \chi_p), \quad e_B = B_{set} - B_{meas} \quad (8)$$

where ω is excitation frequency content, g is the relevant geometry and χ_p represents product-coupling variables. Together these equations identify what must be instrumented and tested.

EM stabilisation measurement programme

The EM effect is treated as an open experimental question. The measurement chain is fixed: field amplitude, frequency content, spatial gradient, registered cut-zone position, product response, and change in cut-zone disturbance. Testing runs in three steps. Step 1 maps the field with no product, establishing baseline amplitude, spectrum, gradient, temperature rise, EMC behaviour and repeatability over the cut-zone volume. Step 2 repeats the mapping with approved fixtures in place, with geometry and sensor positions under configuration control. Step 3 repeats the same field states with product under defined SKU conditions and compares the pre-registered response measures with the Step 1 and Step 2 baselines. For each test condition the EM state and the product response are recorded as:

$$\Phi_{EM} = [B_{amp}, f, \nabla B, x_c], \quad y_{SKU} = [F_{rms}, a_{rms}, e_{path}, T_s, Q, \hat{\varepsilon}_{SKU}] \tag{9}$$

where B_{amp} is local field amplitude, f is frequency content, ∇B is spatial gradient, x_c is cut-zone position, F_{rms} is force disturbance, a_{rms} is vibration disturbance, e_{path} is path error, T_s is local temperature, Q is a pre-registered quality measure and $\hat{\varepsilon}_{SKU}$ is a dielectric-variability indicator built from local temperature rise, field spectrum and SKU salinity and moisture mapping. Sensory or visual grading within Q is blinded and defined before testing. No correlation threshold is assumed in advance.

The working hypothesis is impedance shaping. The ring is proposed to change the local mechanical impedance at the cut through two routes: Lorentz-force coupling to the tool or fixture, and low-level dielectrophoretic effects on the product. Prediction P-1 passes only if the ring produces a measurable, repeatable local field that correlates with a reduction in one or more pre-registered disturbance measures, without breaching thermal, EMC, hygiene or safety limits. The hypothesis is rejected for a product condition if no safe, repeatable and relevant field state can be shown, or if any apparent effect cannot be separated from thermal, fixture, path or measurement artefacts.

Dielectric variability is a gate in its own right. If $\hat{\varepsilon}_{SKU}$ shows local heating spikes, non-linear coupling or drift outside the registered envelope, the G-EM and G-THERM gates force the EM commands into safe back-off, and the EM envelope for that product is narrowed or suspended until the cause is resolved through the measurement programme.

Parameterised analyses

Three deterministic proxy analyses were run from the paper's stated assumptions to expose the main dependencies before hardware exists. (a) Contact stress: a 100 N normal load spread over effective contact patches of 100 mm² (concentrated, legacy case) and 240 mm² (distributed, PICCOLO case). (b) Vibration: a single-degree-of-freedom model with a 2.5 kg reduced mass and a 45 Hz nominal mode, at damping ratios ζ of 0.03 and 0.12. (c) Thermal conditioning: a first-order model of near-surface temperature rising from 2 °C toward an 8 °C conditioning band, with time constants of 20 s for salmon, 35 s for chicken breast and 55 s for beef striploin. These are parameterised models, not finite-element, fluid-dynamic or food-safety analyses. Their outputs are compared with instrumented prototype measurements before any performance inference is made.

Staged validation and instrumentation

Development runs in four phases so that an unproven subsystem cannot hide inside an integrated machine (Figure 7). Phase 1 tests field mapping, thermal response, actuator stability, sensing and hygienic materials separately. Phase 2 integrates the approved subsystems with defined products and a controlled measurement plan. Phase 3 moves only validated functions to a pilot line for process-capability, cleaning, operator and maintenance assessment. Phase 4 is a certification and commercial decision point. Phase 1 and 2 machines use manual SKU changeover; adaptive SKU switching is a Phase 3 to 4 objective.

The Phase 1 to 2 instrumentation is the minimum evidence set for the gates: field amplitude and spectrum, spatial gradient and registered position, temperature rise, EMC observation, force disturbance, vibration disturbance, path deviation, product temperature, synchronised timestamps and pre-registered quality samples. Later studies may add vision-based trim mapping, high-volume mass distribution, operator-intervention logs, sanitation resource metrics, maintenance data and cost telemetry. Each subsystem has a gate (G-EM, G-FEED, G-MECH, G-THERM and G-HYG) with defined pass evidence and stop triggers (Appendix B).

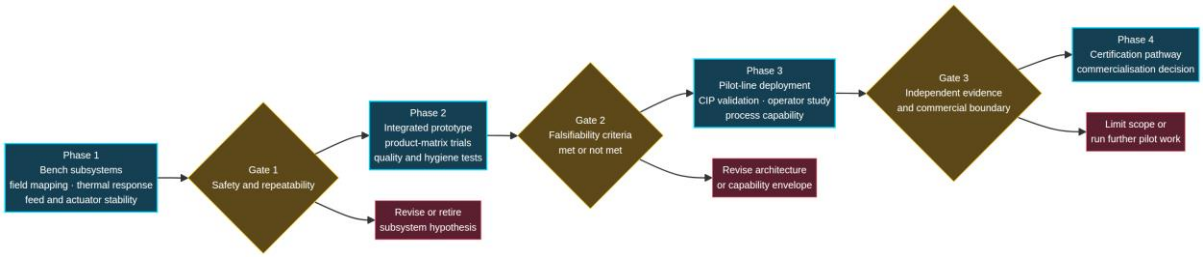

Figure 7. PICCOLO staged prototype and validation pathway. Each gate may lead to progression, architecture revision, scope limitation or retirement of a subsystem hypothesis.

RESULTS AND DISCUSSION

Parameterised analyses

Figure 8 shows the contact-stress proxy. Spreading the same 100 N load over 240 mm² instead of 100 mm² lowers the mean contact stress from 1.0 MPa to about 0.42 MPa, and the normalised peak stress falls by roughly half, from about 1.07 to about 0.51. The load is also carried across a wider zone of the cut. The result shows how strongly cut-zone stress depends on effective contact area, and it supports the design choice to govern load distribution at the cut. Predicting tearing or cut quality from this proxy requires calibration against each product.

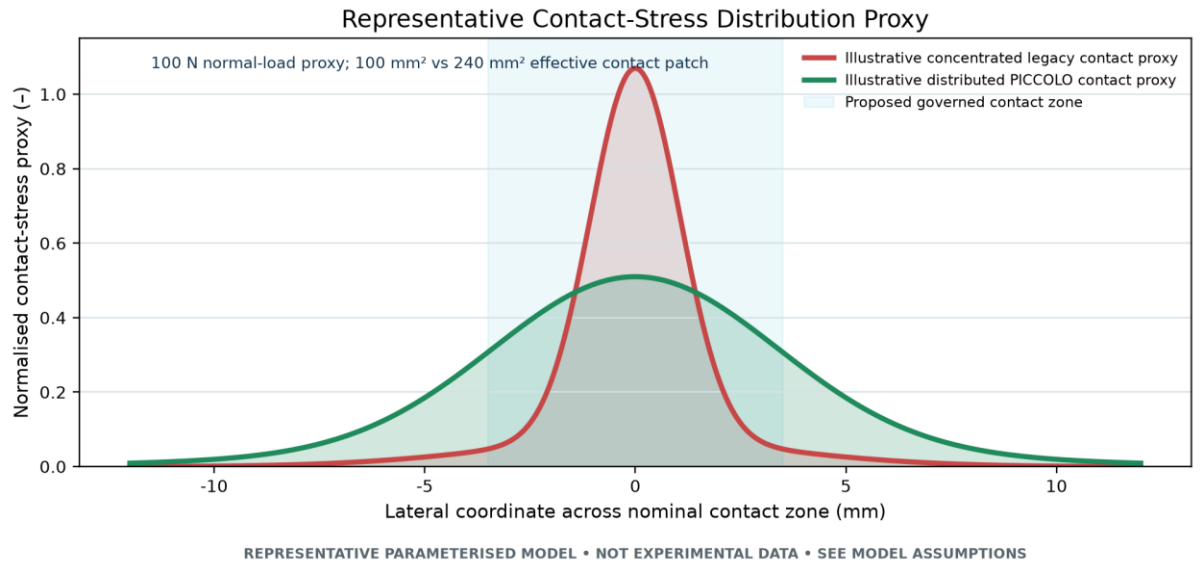

Figure 8. Representative contact-stress distribution proxy. The distributed curve illustrates sensitivity to effective contact-area assumptions only; it does not predict product fracture or cut quality.

Figure 9 shows the vibration proxy. With low damping ($\zeta = 0.03$), the 45 Hz mode is still ringing at about 3% of its first peak 400 ms after a disturbance. With governed damping ($\zeta = 0.12$), the response falls below 5% within about 100 ms. Damping therefore decides how quickly the cut zone returns to a bounded state after a disturbance, which is why damping and actuator rate limits sit in the shared mechanical support layer. The model is a single-mode illustration, not a modal test of a PICCOLO machine.

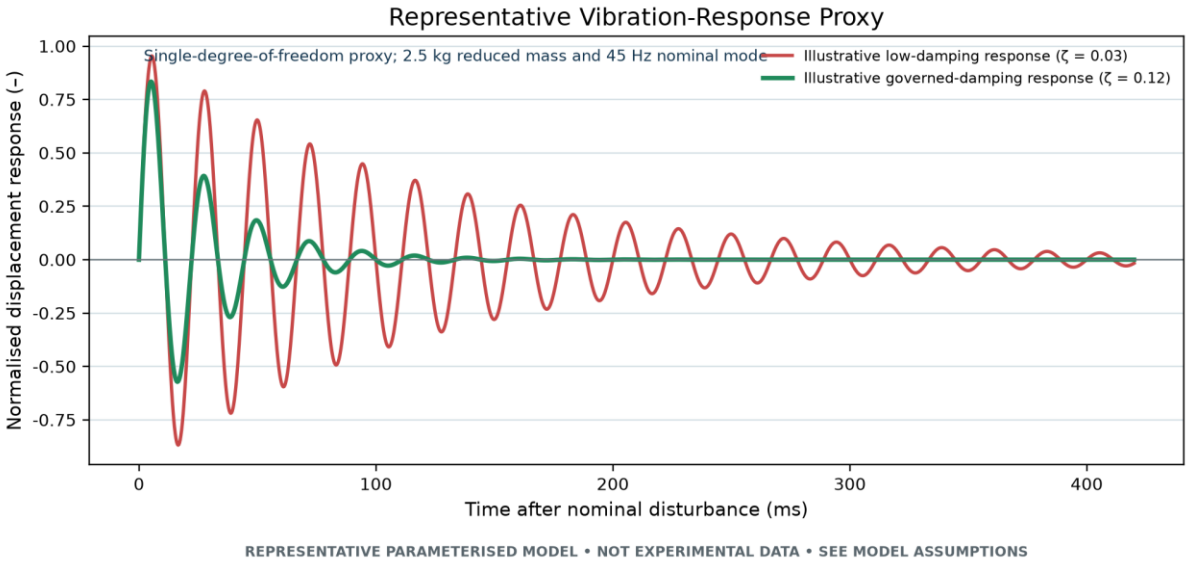

Figure 9. Representative vibration-response proxy for two damping assumptions. The model is a single-degree-of-freedom illustration, not a modal test of a PICCOLO machine.

Figure 10 shows the thermal proxy. Near-surface temperature reaches 95% of its step in about three time constants: roughly 60 s for salmon, 105 s for chicken breast and 165 s for beef striploin. The spread between products is the main finding. A single dwell time cannot suit all three, which supports per-SKU envelopes and the Phase 1 to 2 pre-cut dwell zone with controlled residence time. The model is first-order and makes no food-safety claim.

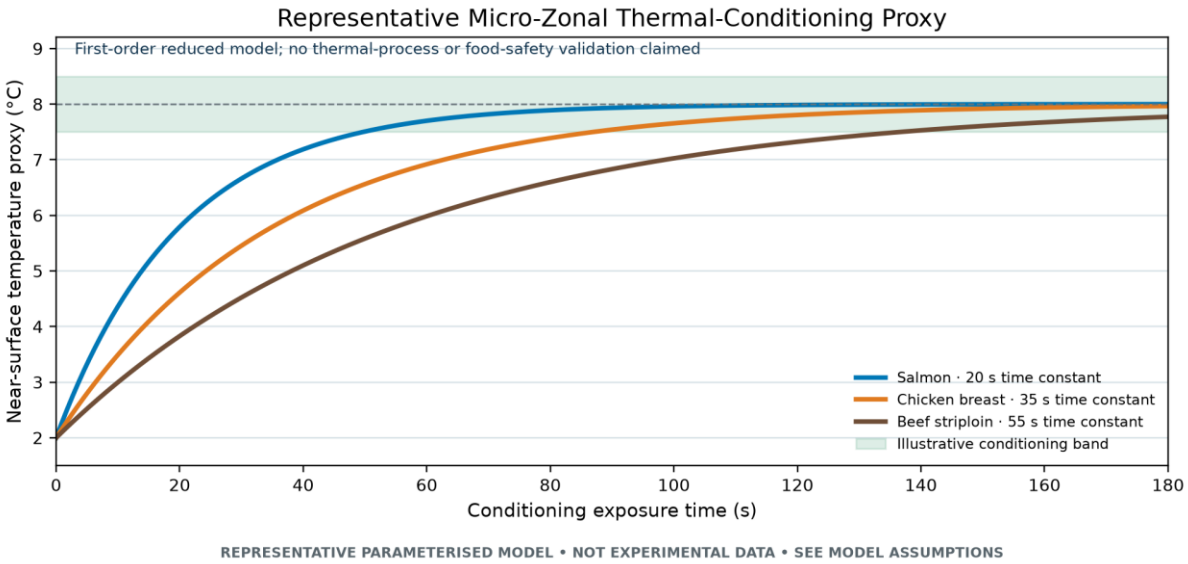

Figure 10. Representative micro-zonal thermal-conditioning proxy for three illustrative SKU response time constants. It is not a food-safety process or product-quality prediction.

Performance targets

Performance is defined in measurable terms (Table 5). Cut placement error is the difference between commanded and inspected cut geometry. Offcut variance is the spread of trim or discarded mass for an approved product. Throughput stability is the ability to stay within a validated process-capability band under defined conditions. Sanitation interval is a verified cleaning measure, not elapsed time. Each value is reported against a defined product, product condition, line rate and inspection method. The headline target is sub-millimetre cut placement for an approved SKU.

Table 5. PICCOLO performance-target definitions and evidence status

Metric	Design target or definition	Evidence status
Cut placement	Sub-millimetre placement accuracy for an approved SKU.	Architecture target; requires metrology and product trials.
Offcut variance	Lower variance than a defined site baseline.	Target; baseline and measurement method required.
Throughput stability	Remain within a validated capability band under approved conditions.	Target; requires line trials and process-capability analysis.
Product-state control	Maintain an SKU-specific response window at the cut zone.	Target; requires thermal and quality correlation.
Sanitation operability	Extend usable production time only where cleanability is verified.	Target; requires cleaning and microbiological validation.

Economic boundary model

No return-on-investment figure is given. Product value, yield, labour profile and hygiene regime differ too much between plants for one number to be meaningful. Instead, Table 6 sets out the variables a host plant fills in: product-value recovery, offcut and rework, sanitation downtime, operator dependency, maintenance and validation, and capital and integration.

Table 6. Economic boundary model variables for host-facility assessment

Variable	Definition	Facility-specific input required
Product-value recovery	Change in saleable mass and grade distribution.	SKU value, yield baseline and inspection data.
Offcut and rework	Mass and labour associated with nonconforming portions.	Trim baseline and rework route.
Sanitation downtime	Lost production time and cleaning resource use.	Validated cleaning cycle, labour, water and chemical use.
Operator dependency	Manual intervention, setup and training requirement.	Observed tasks and labour rate.
Maintenance and validation	Planned inspection, calibration and qualification burden.	Component plan and validation protocol.
Capital and integration	Machine, utility, enclosure and line-integration cost.	Supplier quote and installation boundary.

Comparison with legacy slicers

A legacy slicer can deliver high throughput within a stable product specification. Its process logic sits in fixed geometry, drive settings and line tolerance. PICCOLO brings product state, local field state, thermal state and path limits into the open as controlled variables. The State-of-Cut observer and the multi-sensor control layer are aimed directly at the capability gaps identified by André-Zarna et al.: tactile sensing, intelligence, adaptivity and perception [8]. The phased control path, PID with gain scheduling first and MPC later, matches the maturity picture in Jeong et al., where data-driven analysis is mature and physical AI-enabled automation is early [9]. The comparison defines what must be validated for PICCOLO to justify its use against an existing machine.

Relation to earlier food-processing architectures

PICCOLO is not a copy of earlier work (Table 7). GEMBC established an EM-governed food-matrix and sensing approach for a bowl cutter [19]. GEDSA established adaptive geometry and governed mechanical architecture for food transport [18]. The cheese portioning architecture established controlled separation, predictive feed, thermal conditioning and hygienic topology for a viscoelastic solid [17]. PICCOLO carries selected patterns into an anisotropic meat and fish matrix, where bone position and fibre direction add constraints. Its coupling, safety and hygiene requirements are verified separately.

Table 7. Comparison of PICCOLO with earlier food-processing architectures

Architecture	Primary system framing	Main contribution	Evidence boundary
GEMBC	EM-assisted matrix and sensing	Uniformity and shear	Established machine-specific performance.
GEDSA	Adaptive geometry	Flow stability and volumetric yield	Design targets pending prototype validation.
High-Integrity Cheese Portioning	Thermal conditioning and controlled separation	Friction and geometry	Architecture-specific validation required.
PICCOLO	Anisotropic matrix; micro-zonal thermal, EM and adaptive motion	Stress distribution and disturbance	Paper-specific validation boundary.

Industry alignment and expected workflow

The architecture targets four weaknesses of legacy food machinery: automation, sustainability, quality control and energy efficiency. These follow from the control layer rather than being added features. Controlled separation is intended to cut avoidable material loss. Bounded disturbance is intended to reduce unnecessary mechanical and thermal input. State estimation is intended to replace tolerance-based quality control with recorded operating evidence. Governed actuation is intended to reduce reliance on operator intervention. Each is a mechanism to be measured in SKU-specific trials and host-plant evidence.

The expected line flow is: (1) the SKU is registered with its approved temperature, geometry, inclusion status and specification; (2) the product is pre-conditioned through the approved thermal route; (3) the product enters the cut zone and the permitted EM ring state is set; (4) a closed-loop cut runs with the State-of-Cut observer active; (5) portions and offcuts are logged and Q is recorded against the pre-registered method; and (6) the

cleaning cycle runs to the hygienic plan. Each step needs plant-specific hazard controls, hygiene validation, guarding, record handling and acceptance criteria before operational use.

Falsifiable predictions

Table 8 lists five predictions that a prototype programme can test and reject. Each is pre-registered with its SKU, method, metric and test condition before results are interpreted. One further condition is an eligibility boundary rather than a prediction: if a product needs bone or inclusion avoidance and neither upstream mapping nor a validated constrained specification is available, PICCOLO is not used on that product.

Table 8. Falsifiable PICCOLO architecture predictions

ID	Prediction	Test route	Failure condition
P-1	The EM stabilisation ring can create a measurable, repeatable field-state proxy within the permitted cut-zone boundary.	Instrumented field mapping and repeatability study.	Field state cannot be measured or reproduced within limits.
P-2	A governed feed path can meet the pre-specified cut-placement criterion for an approved SKU.	Metrology and product-trial comparison.	Placement error fails the registered criterion.
P-3	Combined sensing and actuator governance can remain stable under registered disturbance conditions.	Controlled disturbance and fault-injection trial.	Instability, unsafe response or non-recoverable variance occurs.
P-4	Micro-zonal conditioning can correlate a measured local product state with an approved quality response.	Thermal mapping and blinded quality assessment.	No repeatable correlation, or an unacceptable quality or safety effect.
P-5	The selected product-contact topology can satisfy its defined cleanability verification route.	Residue, drainage, CIP and microbiological assessment.	The documented cleanability criterion is not achieved.

Architecture revision path

A failed gate changes the design. If P-1 or G-EM fails, the EM ring is separated from the mechanical, thermal, feed and hygiene functions, and its geometry, excitation, shielding, instrumentation and coupling hypothesis are revisited in a bounded bench programme. If a safe, repeatable and relevant field state still cannot be shown, the ring is removed from the initial capability claim, and PICCOLO continues as a governed mechanical and thermal platform, provided the remaining subsystems pass their own gates.

If P-4 fails, the thermal method, sensing location, state definition and SKU envelope are revised; if a quality correlation still cannot be shown, conditioning is limited or removed for that product. The same rule applies to every gate: failure narrows the envelope, triggers redesign or retires the function. Appendix A lists the main engineering risks and their mitigations.

Scope of claims

PICCOLO is a proposed architecture. This paper does not report a fabricated machine, demonstrated commercial performance, food-safety certification, pathogen reduction, sterilisation, guaranteed yield gain, universal meat or fish applicability, electromagnetic cutting, worker-exposure compliance or a validated economic return. The EM ring does not replace a blade, a hygiene programme, guarding, inspection or regulatory approval. All targets in this paper are design targets.

CONCLUSION

This paper set out PICCOLO, a governed electromagnetic portioning and slicing architecture for industrial meat and fish processing. The starting point is that meat and fish are variable, anisotropic materials. Fibre direction, connective tissue, fat, moisture, temperature and bone position change how each piece responds to a cut, and the literature on fish cutting, meat protein behaviour, meat rheology and meat-processing robotics points the same way. A slicer that runs from fixed geometry and programmed motion absorbs that variation through tolerance and trimming. PICCOLO measures it and acts on it.

The architecture replaces a force-only view of slicing with a coupled state model. Product condition, cut path, temperature, local field state, vibration and hygienic geometry are handled together by a two-layer control system. Five subsystems carry the work: the EM stabilisation ring, predictive feed and indexing control, actuator governance, micro-zonal thermal conditioning and hygienic surface topology. Shared mechanical support provides damping, isolation and rate limits for all five. A State-of-Cut observer, sampling at 500 to 1,000 Hz with a response target below 20 ms, is intended to let the machine correct a cut while it is happening.

The EM ring is the distinctive element, and its role is defined narrowly. It is proposed to shape local mechanical impedance at the cut through Lorentz-force coupling and low-level dielectrophoretic effects. A three-step measurement programme, with dielectric variability as a measured gate, confirms or rejects that hypothesis for each product. If the ring fails its gate, PICCOLO continues as a governed mechanical and thermal platform, provided the remaining subsystems pass their own gates.

The parameterised analyses show three things. Cut-zone stress depends strongly on effective contact area. Damping decides how fast the cut zone settles after a disturbance. Thermal conditioning time differs widely between salmon, chicken breast and beef striploin, which supports per-product envelopes and a pre-cut dwell zone in the early phases. The contribution of this paper is a structured, testable architecture. It provides five coordinated subsystems, an explicit product envelope, measurable performance definitions, a hygiene verification route, a plant-specific economic boundary model and five falsifiable predictions, each tied to a gate. Every gate has a defined outcome on failure: redesign, a narrower envelope or retirement of the function. The upstream bone-mapping and sensing technologies the architecture depends on are already in commercial use.

The next step is Phase 1 bench work: unloaded field mapping of the EM ring, actuator and vibration characterisation, thermal response trials for the three starting products, and first tests of the State-of-Cut observer against registered reference observations. Those results decide which functions move into an integrated Phase 2 prototype, and they set the first measured envelopes for salmon, chicken breast and beef striploin.

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Appendix A. Engineering Risk Register

Table A1 records the main concept-stage risks. It supports, and does not replace, a formal product-safety, machine-safety, EMC, food-safety or regulatory risk assessment.

Table A1. PICCOLO concept-stage engineering risk register

Category	Risk	Consequence	Mitigation and gate
EM and EMC	Unwanted field coupling, heating or emission	Safety, quality or compliance concern	Bench mapping, shielding study, EMC test, safe-state interlock.

Mechanical	Actuator or fixture resonance	Geometry error, product damage or unsafe motion	Modal characterisation, rate limits, guarded fault testing.
Thermal	Over- or under-conditioning	Smear, tear, moisture change or quality loss	SKU-specific thermal mapping and independent quality review.
Hygiene	Residue trap or degraded cleanability	Sanitation failure or contamination risk	Hygienic design review, residue challenge, CIP verification.
Control	Sensor drift or unstable state estimate	Incorrect command or process variance	Calibration plan, diagnostic coverage, safe hold or reject logic.
Commercial	Benefits not sufficient for facility economics	No viable deployment case	Facility-specific boundary model and pilot evidence.

Appendix B. Subsystem Risk Gates

Table B1 turns the risk register into explicit subsystem decision gates for the concept stage.

Table B1. PICCOLO subsystem-specific risk gates

Gate	Required pass evidence	Revision or stop trigger
G-EM	Measured field-state repeatability without thermal, EMC or safety-limit breach.	Fail if no safe, repeatable, relevant local field state is shown, or if $\hat{\varepsilon}_{SKU}$ indicates localised RF/EM heating spikes or non-linear coupling. Force EM safe back-off; narrow or suspend the SKU EM envelope.
G-MECH	Registered modal, path and safe-state criteria are met.	Resonance, force excursion or unsafe response exceeds criterion.
G-FEED	Predictive feed meets registered placement and hold or reject criteria.	Path or controller-stability criterion fails.
G-THERM	Conditioned product state correlates with approved quality response and safety boundary.	Fail if thermal-state control is not repeatable or $\hat{\varepsilon}_{SKU}$ indicates localised RF/EM heating spikes. Force EM safe back-off; narrow or suspend the SKU EM envelope and remain in the Phase 1–2 pre-cut dwell configuration.
G-HYG	Registered cleanability and drainage verification route is passed.	Residue, pooling, access or cleaning-verification criterion fails.