Evolving Manufacturing

SynaCore

Whitepaper

Pre-Qualification (v1.6)

The transition to model-based qualification

Built on the SynaCore AM-DT digital twin and surrogate AI

Conventional	Point design · prescriptive · lock KPVs · physical testing
Advanced	Part family · delta qualification · equivalency · process qualification
Innovative ◀ **OUR TARGET**	Model-assisted · NDE-driven · data-enabled · no lock KPVs

SynaCore AM-DT
Multi-scale physics
+ Surrogate AI
calibrated · validated · prequalified

→ New Erea

DQ: virtual multi-physics design validation
IQ: digital mirror of the AM equipment
QQ: adaptive process control + calibration
PQ: virtual pre-certification + DT-DPP traceability

SynaCore
Drive physical manufacturing with virtual intelligence
www.synacore.net

Preface

To change the status of Print in Hours, Qualify in Years

PREFACE

The Scissors Gap Between Making and Certifying

A metal part can be printed in a matter of hours. Certifying that same part can take years. Anyone who has shepherded an additive manufacturing component through qualification knows this asymmetry intimately.

In aero engines, defense systems and high-end equipment, additive manufacturing has crossed the threshold of *can we use it* and entered the far harder competition of *can we use it at scale. A*t this stage, the decisive factor is no longer the forming capability of the printer. It is whether the certification system can **mass-produce trust at an industrial rhythm**.

The scissors gap between surging manufacturing capability and lagging certification capability is the concentrated expression of a universal constraint on AM industrialization: **design and printing are measured in days; certification is measured in years.**

Why is the gap so persistent? Because the evidence that certification consumes is static, while the process windows that manufacturing produces evolve continuously. Qualification frameworks were built for a world of frozen processes and stable designs — a world that additive manufacturing, with its multi-physics coupling and cross-scale behavior, simply does not inhabit. Every parameter refinement, every machine upgrade, every powder batch change threatens to invalidate accumulated evidence and restart the clock.

When even the most advanced manufacturer in the world plans its future around shrinking certification from years to months, we should read it as a signal: the bottleneck of our industry has moved from the factory floor into the evidence chain. Solving it requires not faster testing, but a fundamentally different way of producing trust.

Five Structural Bottlenecks of Statistical Qualification

The reason certification cannot keep pace with manufacturing resolves into five structural problems :

1- Diseconomies of scale in physical evidence production. The number of physical specimens grows linearly—even superlinearly—with the statistical confidence demanded. The marginal cost of physical certification cannot be amortized by volume; if anything, confidence requirements rise as batches grow. The digital twin does not eliminate this statistical reality, but it shifts the marginal cost of evidence from physical destruction to computation and calibration.

2 · Knowledge does not transfer. Physical evidence is bound to the machine × material × part triple. Change the machine, and qualification starts over.

3· The rigidity of the process freeze. Evidence validity depends on frozen parameters; any change triggers tiered requalification. This is why every act of process innovation must run a new round of certification tprocess.

4 · Organizational knowledge is never assetized. This is the most underestimated item on the challenge list: additive product incorporation experience is hostage to a rapidly changing workforce. The rationale behind a process window — why this laser power, this scan strategy, this layer thickness — lives largely in the minds of senior engineers, not in reusable model assets. When people leave, the decision history, the failure-analysis intuition and the cross-project craft leave with them.

5 · The legacy of point solutions. AM was introduced machine by machine, part by part, document by document. Islands of equipment, parts and process files with no standardized additive thread — both the historical cause of the first four problems and the organizational soil that keeps reproducing them.

From Constraint to Accelerator

A prediction without calibration is a claim; a prediction with a disciplined calibration protocol is evidence. We hope you find it is useful about SynaCore AM-DT Calibration Protocol — its architecture, workflow, data discipline and release gates — because this is where digital twins earn the right to certify.

I want to be candid about our position: the transition to model-based qualification will not abolish physical testing — it will finally make physical testing intelligent. Experiments stop being disposable proofs and become calibrating and validating investments whose value compounds. Every build, success or failure, becomes an appreciating asset of knowledge rather than a sunk cost of compliance.

At SynaCore, we have spent years building the physics foundation models, the surrogate AI acceleration and the calibration discipline that this transition demands — rooted in the fundamental research of A*STAR's IAIC and hardened through close collaboration with manufacturers. This whitepaper shares where we believe the industry must go, and the practical protocol by which any manufacturer can begin the journey today.

Certification should not be the price of innovation. Done right, it becomes the currency of trust that lets innovation scale. I invite you to read on — and to join us in building the standards, the protocols and the shared confidence that additive manufacturing deserves.

XiaoYan (Kitty) Wang

CEO of SynaCore Pte. Ltd.

A Global Standards Movement

Pre-Qualification on the International Agenda

SECTION 01

SECTION 01 · A GLOBAL STANDARDS MOVEMENT

Global Consensus: Qualification is Becoming Model-Based

The signals from the world's leading institutions have become unambiguous. ASTM is developing guidelines for model-based qualification and certification of AM components. The National Institute of Standards and Technology (NIST) has stated that "it is very important that industry finds alternatives to conventional qualification methods; these are likely based upon validated models, probabilistic methods, and part similarities." NASA is funding the development of model-based certification for additively manufactured components destined for its rockets and spacecraft.

Read together, these positions amount to a global consensus: **model-based qualification is urgently needed by industry, and the transition from experimental to model-based evidence is the accepted direction of travel.**

For certification societies and regulators, the shift is equally pragmatic: a qualified model with a documented validation pedigree offers something a stack of test reports never can — an auditable, computable chain of reasoning from process to performance, open to interrogation rather than merely to inspection.

Question:

Why are standards organizations moving on model-based qualification now — what changed?

Answer:

Two curves crossed. On one side, the cost of statistical, specimen-based qualification kept rising as AM moved from prototypes to flight-critical and safety-critical parts. On the other, digital twin fidelity matured to the point where physics-based models can predict the very quantities qualification requires — distortion, porosity, microstructure, mechanical properties — with quantifiable accuracy. When the evidence can be computed, audited and bounded, the case for certifying models alongside parts becomes undeniable.

The AM complexity problem

- Different powders, machines, scan strategies and complex geometries
- Quality inconsistencies make part-by-part certification a daunting task

Experimental Q&C is costly & lengthy

- Every test costs surveyor/technician time, coupons, equipment
- Build → Certification wall → Part in Service

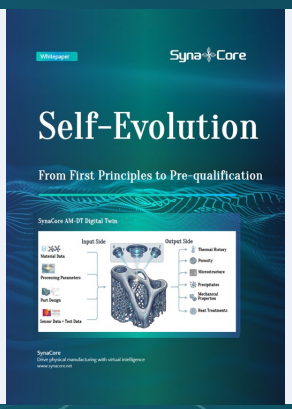
Global consensus: go model-based

- NIST: developing guidelines for model-based Q&C of AM parts
- DNV GL: alternatives to conventional qualification are needed
- NASA: funding model-based certification for rockets & spacecraft

Singapore is positioned to lead: A*STAR IAIC's spon off SynaCore AM-DT is the only integrated, monolithic platform that predicts all qualification quantities at once — thermal history, microstructure, defects, mechanical properties, residual stress and distortion.

Find more introduction in SynaCore previous whitepaper of <Scale up> and <Self-Evolution>.





SECTION 01 · A GLOBAL STANDARDS MOVEMENT

Global Consensus: Certification Must Evolve

A Signal from the field:

At a keynote at ASTM's International Conference on Additive Manufacturing (ICAM), a senior additive leader from one of the world's largest aerospace and defense companies put two curves on screen.

The first sprinted: laser power doubling and build volume tripling every four years, with new architectures and an ever-widening alloy palette. The second was nearly flat: qualifying a single high-criticality part still costs double-to-quadruple-digit dollars and takes one to three-plus years.

Between the two curves, demand is no longer waiting. Aging fleets need parts their supply chains no longer make; attritable (low-cost, loss-tolerant) platforms, additively-made heat exchangers and grounded engines all queue for qualified components — at the speed of relevance, in the presenter's words.

The bottleneck has moved off the factory floor and into the evidence chain. Print-and-break qualification, built for frozen processes, cannot chase a technology that reinvents itself every cycle. Certification must evolve — from a post-hoc verdict into evidence produced ahead of the build. That is the transition this whitepaper addresses: how certification learns to run.

From signals to pre-qualification — the chain of trust.

THE EVIDENCE CHAIN — ONE BUILD, END TO END

01 · SENSE
Sensors record every layer; a configuration fingerprint binds Machine, Powder-Lot, Build and Model-Version IDs.

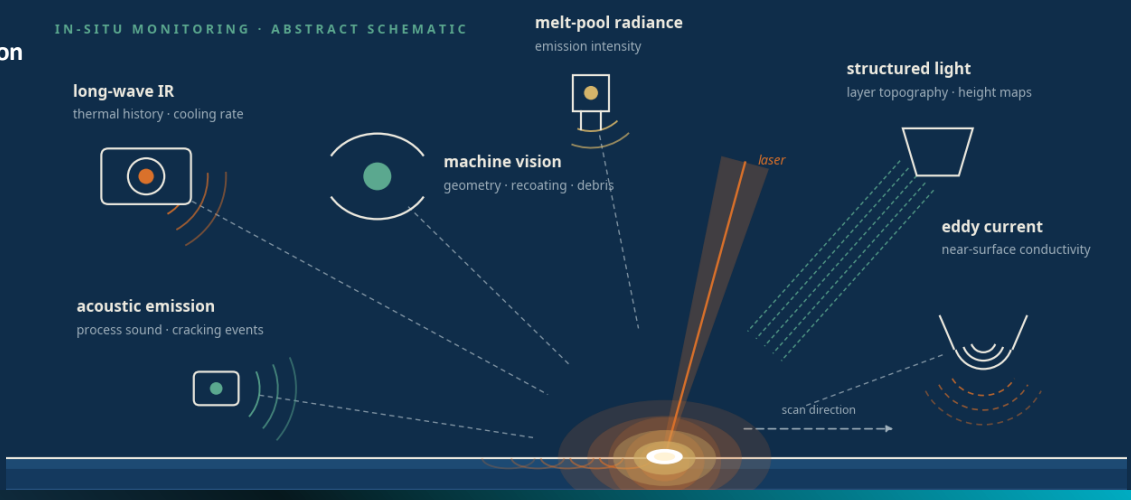
02 · FUSE
Co-registered signals become a layer-wise anomaly record — the measured half of the digital twin.

03 · CALIBRATE
Multi-scale physics plus surrogate AI, validated against test results.

04 · PRE-QUALIFY
Predict inside the validated domain; re-test only the delta. The part is born pre-qualified.

What changes for qualification

In-situ data alone is not qualification — but it is the missing measured half of the digital twin. Fused with calibrated physics and governed AI, each build yields a verifiable evidence package: what the sensors saw, what the model predicted, what the CT confirmed.



Sensed, fused, calibrated, pre-qualified — trust becomes a property of the process, not a post-hoc test.

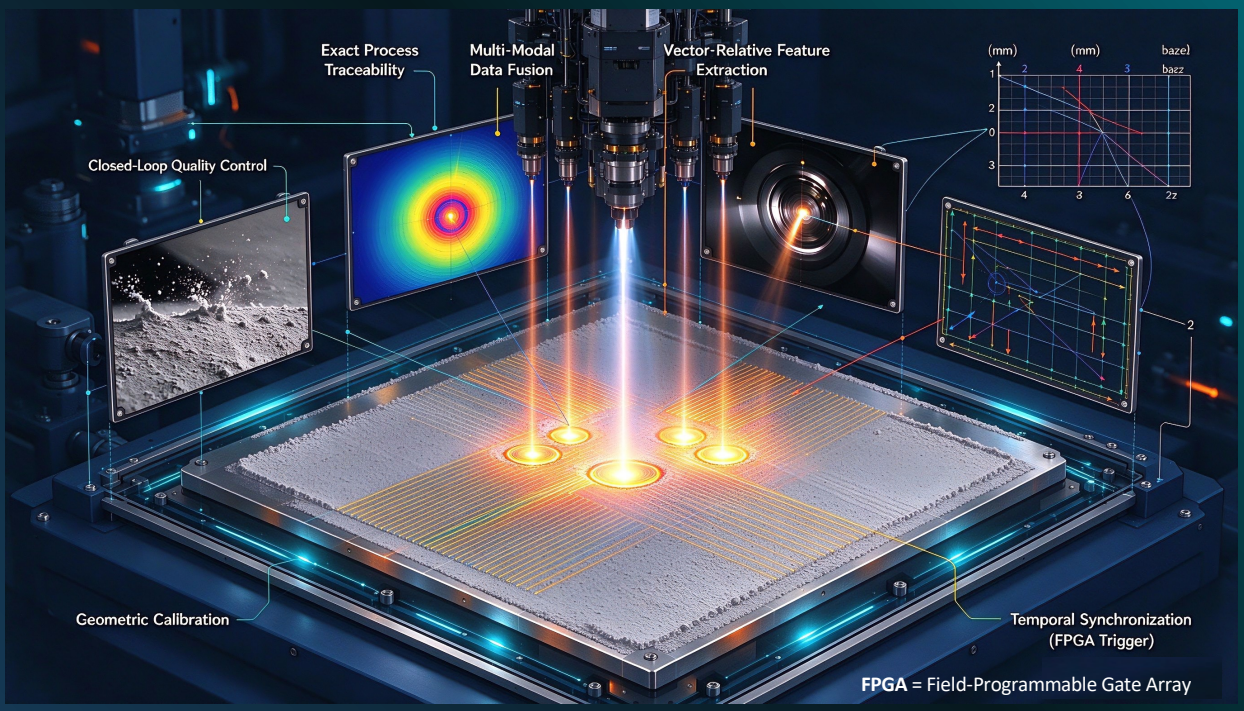
SECTION 01 · A GLOBAL STANDARDS MOVEMENT

Foundation for Scalable Trust: Toolpath-Coordinate Alignment & Cross-Platform Transfer

01 · The Data Alignment

To make model-based qualification viable, in-situ sensing data cannot exist as isolated, unaligned 2D images. It must be anchored to physical reality — in the toolpath's own coordinates.

All multi-modal sensor data — melt-pool thermal emission, full-plate thermal imaging, recoat-defect detection — is co-registered directly to toolpath coordinates.



Multi-modal layer data are co-registered onto the toolpath vector frame — every pixel maps to the exact laser vector that made it.

Feature-by-feature comparability

Mapping every sensor pixel to the exact laser vector that created it enables precise, feature-by-feature comparison between builds—a standardized, immutable data stream for feeding and calibrating the SynaCore AM-DT physics engine.

To break the circular dependency between sensor data and physical truth, initial calibration relies on targeted destructive testing (e.g., CT, EBSD) to establish the ground truth anchors. Once anchored, toolpath-aligned in-situ data exponentially expands the value of these limited physical tests across the entire build volume.

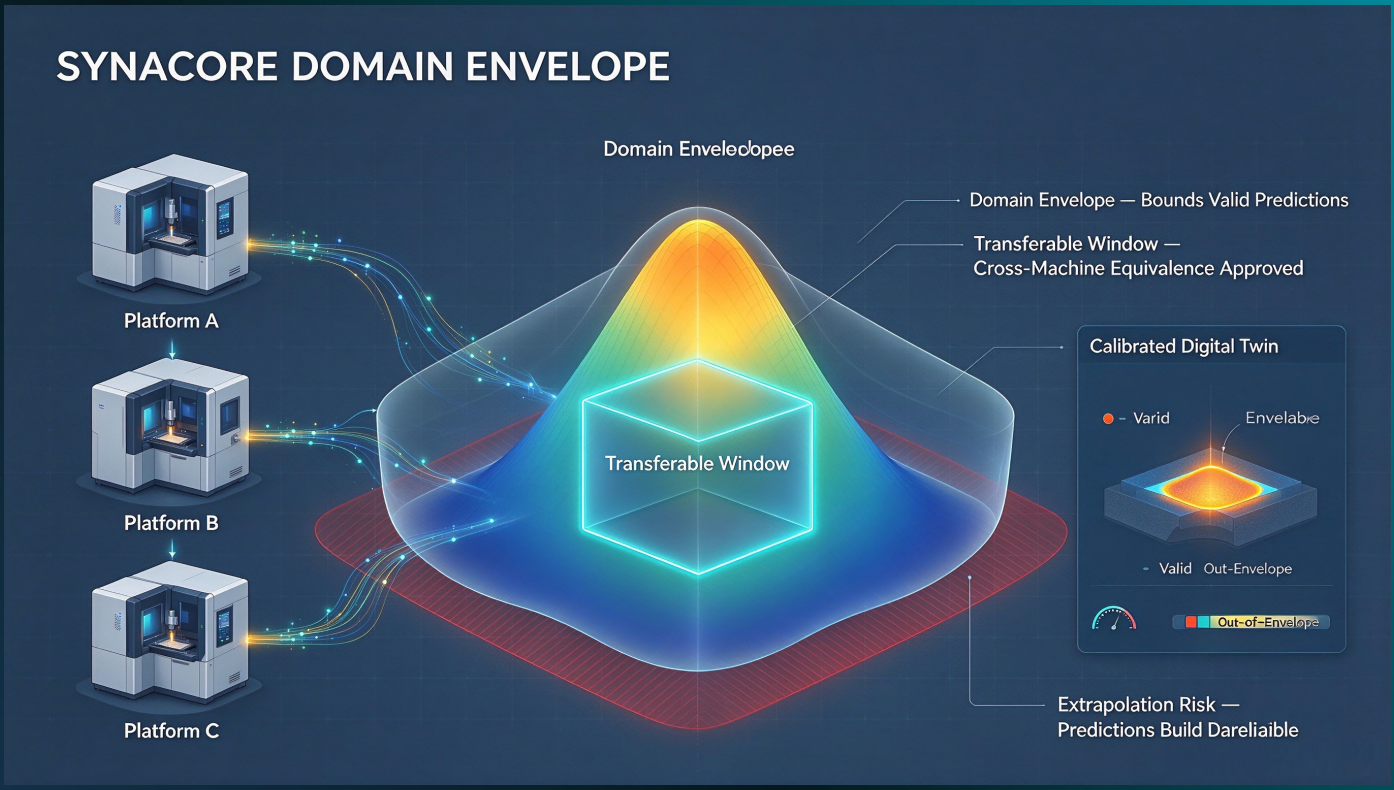
02 · Cross-Platform Transfer — Demonstrable Equivalence

A qualified process window is only valuable if it can travel. The industry is demonstrating that a single toolpath intent can yield equivalent material properties across different machines.

Transferable windows

Instead of requalifying from scratch, SynaCore's Domain Envelope integrates cross-platform data to define a transferable window — differences between machines are measured, understood, and mathematically approved.

Transitioning from isolated machine-specific evidence to a unified, certifiable digital ecosystem.



SYNACORE DOMAIN ENVELOPE

Instead of requalifying from scratch, SynaCore's Domain Envelope integrates cross-platform data to define a transferable window—differences between machines are measured, understood, and mathematically quantified and compensated. Cross-machine equivalence is then empirically validated and approved within this bounded window.

03 · SynaCore Integration — Simulation-First, Test-Confirmation

When toolpath-aligned in-situ evidence converges with SynaCore's calibrated digital twin, the qualification bottleneck breaks.

Delta qualification

Changes to machine or powder are evaluated mathematically inside the validated domain. Evidence is strengthened by removing irrelevance — not by repeating redundant physical tests.

Supply-chain scaling

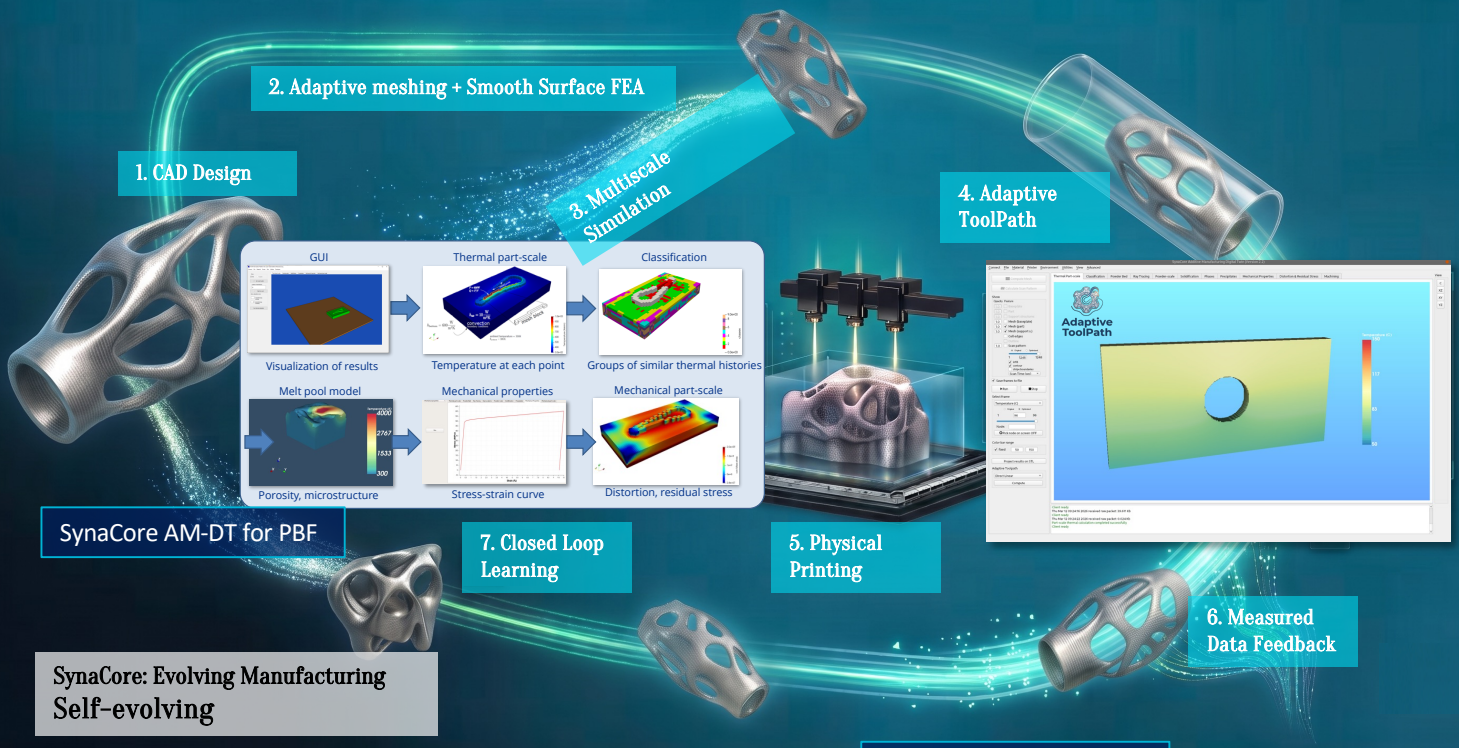
Certification is freed from geography. A model validated in one facility becomes a portable, verifiable asset — a digital birth certificate — that can be executed globally.

BOTTOM LINE FOR MANUFACTURERS

Open toolpath control, qualified process windows, and toolpath-aligned in-situ evidence make machine equivalence demonstrable. This is the infrastructure required to unlock the scaling of the additive manufacturing supply base.

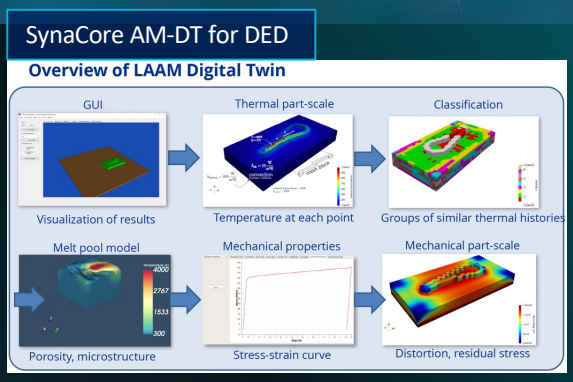
Moving towards a shared vision

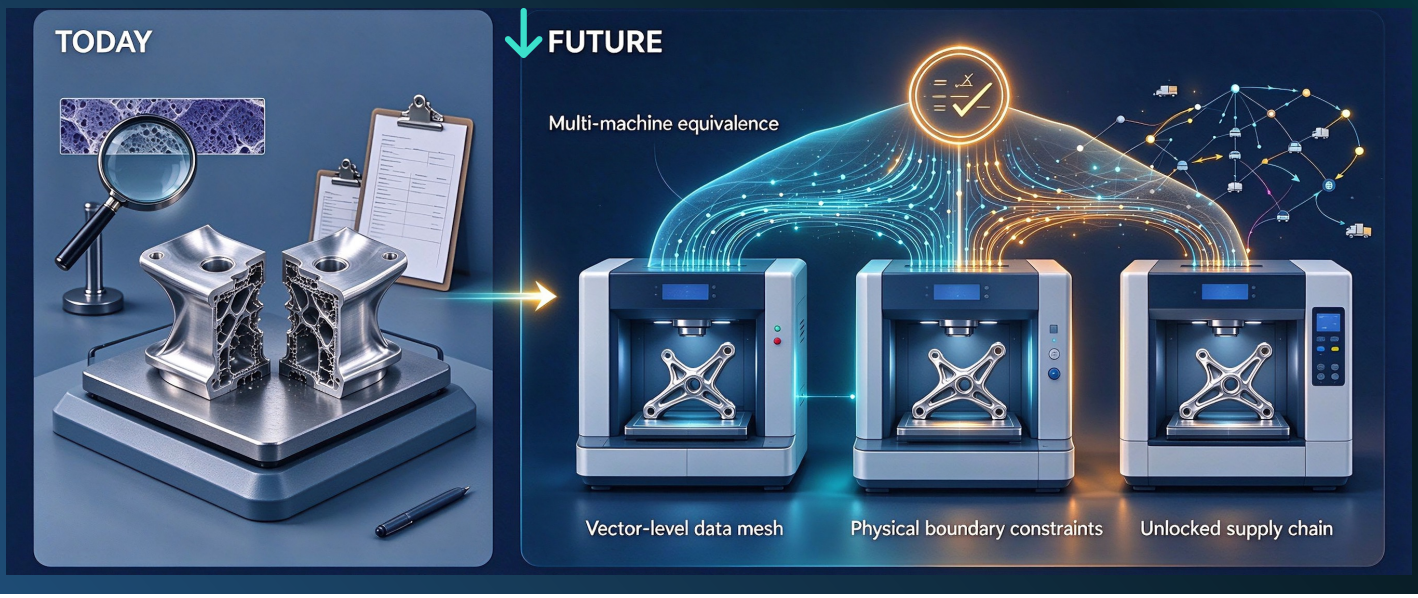
Evolving Manufacturing



Moving towards a shared vision:

Moving towards a shared vision: Future 3D printing will drastically reduce its reliance on "print-and-destroy" sampling. Instead, by leveraging cross-platform accumulated vector-level data and strict physical boundary constraints, we can mathematically demonstrate that different machines produce statistically equivalent parts. This generates a "digital evidence package" that is audit-ready and pre-qualified—enabling regulators to grant final approval with minimal redundant testing, thereby substantially unlocking the capacity of the supply chain.





A New Work Item for Digital Qualification Using Digital Twins

This consensus is now taking institutional form. A New Work Item Proposal — *Additive Manufacturing – Qualification Principles – Method for Digital Qualification of Metal 3D Printed Components Using Digital Twins*— was tabled in August 2025, convened by Dr. Guglielmo Vastola, CTO of SynaCore Pte. Ltd. The proposal begins with a Technical Reference (TR), followed by international extension in close cooperation with ASTM in the United States.

Scope of the Technical Reference

1 · Identification of **Digital Twin software architectures** suitable for model-based certification — what a digital twin must be, not merely what it must show.

2 · Identification of the **physical quantities sufficient to qualify** a 3D printed component — the minimum predictive basis on which certification can responsibly rest.

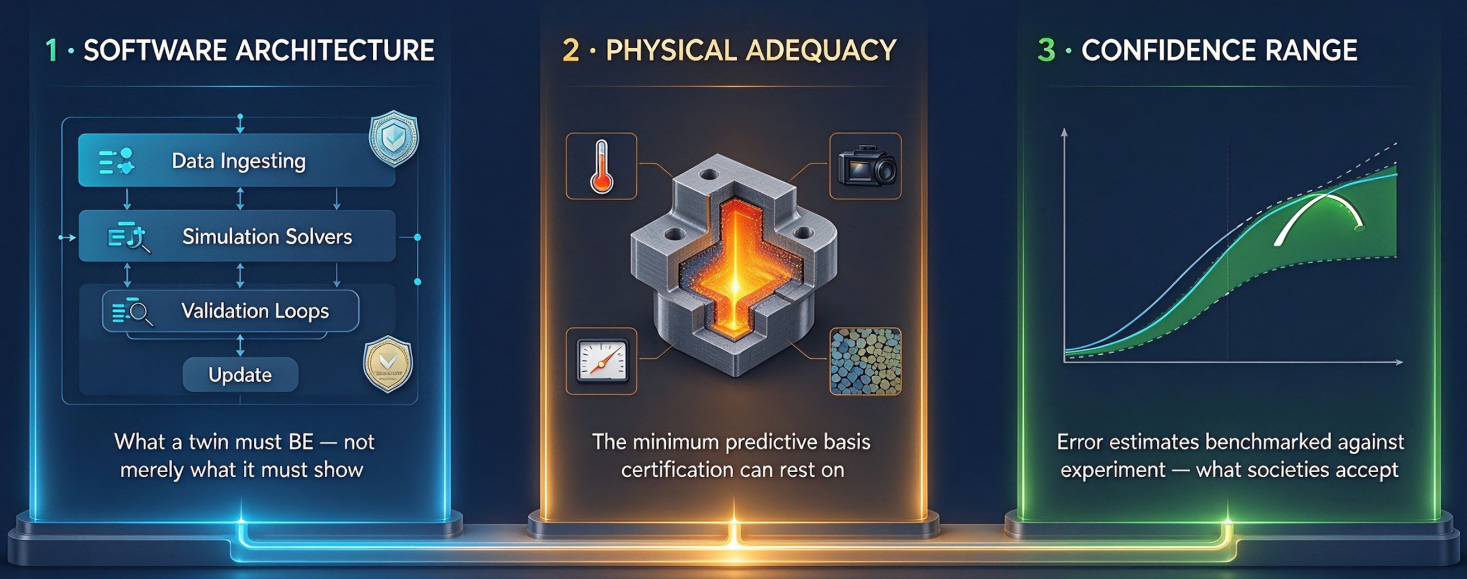
3 · Identification of the **acceptable confidence range** — the error estimates in model predictions, benchmarked against experimental testing, that certification societies deem acceptable.

A working group that spans the entire chain of trust

The proposed working group deliberately assembles every constituency whose assent pre-qualification will ultimately need: classification societies and certification bodies (**American Bureau of Shipping, DNV, Bureau Veritas**); regulators and public end users (**Maritime and Port Authority of Singapore, Land Transport Authority, Singapore Armed Forces**); industry associations (**Singapore Manufacturing Federation, Association of Singapore Marine Industries, Singapore Shipping Association**); manufacturers and service providers (**ST Engineering, Alstom, Tru-Marine, OMS Group, Pelagus 3D, Factorem, Forefront Additive Manufacturing**); research institutes (**A*STAR IAIC, IMRE, SIMTech**); and **ASTM** itself.

THREE FOUNDATIONS OF MODEL-BASED CERTIFICATION

What a digital twin must be, must know, and must admit



SECTION 01 · A GLOBAL STANDARDS MOVEMENT

What Must a Digital Twin Predict — and What Is It Worth?

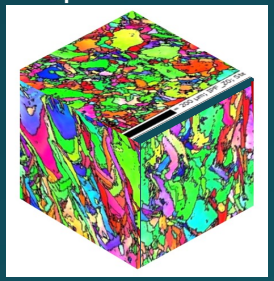
The New Work Item grounds its ambition in a concrete case study from the maritime sector. The table below lists the tests a classification society requires to qualify an AM component today. The premise of model-based qualification is exacting and simple: **for each test, the digital twin must be able to predict the same quantity using physics-based models.**

Qualification Test	What It Establishes	Digital Twin Counterpart
Visual / dimensional / penetrant / radiographic inspection	Geometry, surface and internal integrity against acceptance criteria	Geometric & defect prediction at part scale
Density testing & metallographic examination	Porosity level, lack of fusion, microstructural soundness	Melt-pool & solidification modelling of porosity and microstructure
Chemical analysis	Composition conformity of the as-built material	Process-aware composition & contamination tracking
Tensile / Charpy / hardness / bend tests	Mechanical performance of coupons and AM parts	Microstructure-to-property prediction incl. scatter
Functional test	Fitness for service of the finished component	Multi-physics performance simulation & virtual verification
Full matrix, PBF & DED, class & non-class	Complete qualification dossier for the component	One integrated platform predicting all quantities simultaneously

The dollar value of going digital: ~50× lower cost per evidence point

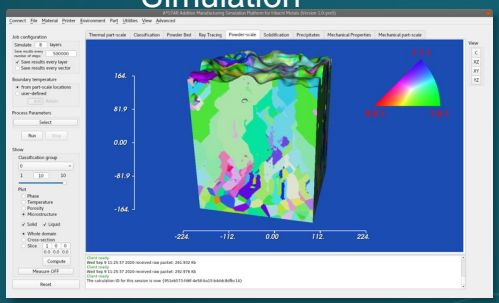
Take microstructure characterization as a worked example. The experimental route costs roughly **US$1,000 for a short build** (powder, machine time at ~US$100/hour, operator), **US$100 to prepare** the sample and **US$200 to characterize** it. The digital route runs the same prediction on a high-end cloud workstation in about eight hours — an order of **US$10 of compute plus software**. Across the dozens of evidence points a single qualification consumes, digitalization converts a linear cost of compliance into a near-marginal cost of computation.

Experiment



→

Simulation

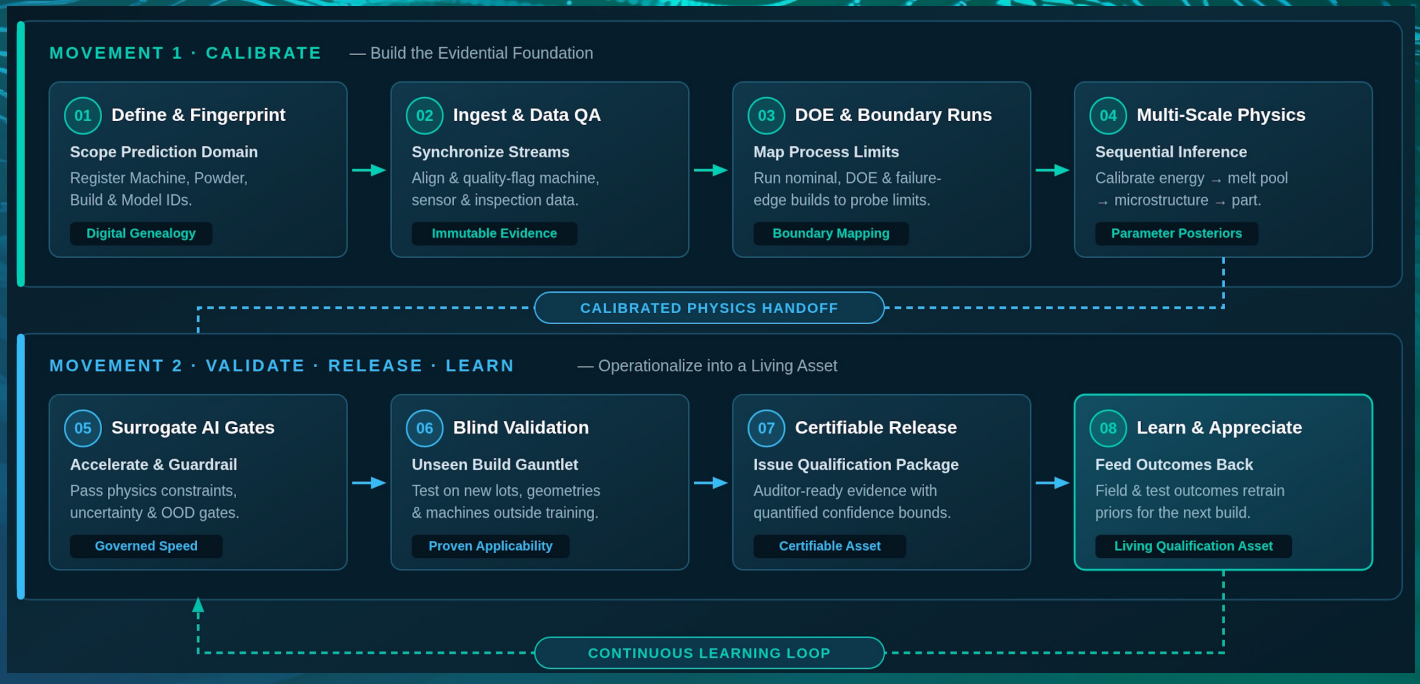


Two questions remain deliberately open for the working group: What accuracy must models demonstrate to be acceptable as qualification tools? And can experimental tests be removed entirely — or should industry converge, for example, on a fifty-fifty blend of experiment and modelling? Both questions point to the same technical heart: **calibration**. That is where we turn next.

The Calibration Protocol

Build the Trustworthy Pre-Qualification

SECTION 02



SECTION 02 · THE CALIBRATION PROTOCOL

From Locked Configurations to Validated Operating Domains

A digital twin is only as credible as its calibration. Pre-qualification cannot rest on a one-off demonstration of accuracy; it must rest on a **protocol** — a repeatable discipline that binds every prediction to physical evidence, quantifies its uncertainty, and states precisely where it ceases to apply. The SynaCore AM-DT Manufacturer-Led Calibration Protocol is designed to convert every build into exactly that: a controlled, traceable act of evidence production.

Its purpose is qualification freedom. Today, certification freezes a configuration; the protocol replaces that frozen point with a **validated operating domain** inside which manufacturing is allowed to breathe, improve and evolve.

TODAY · LOCKED CONFIGURATION

- Material specification
- Part design
- Process parameters
- Machine configuration

A change in any link can trigger repeated testing and a complete requalification cycle.

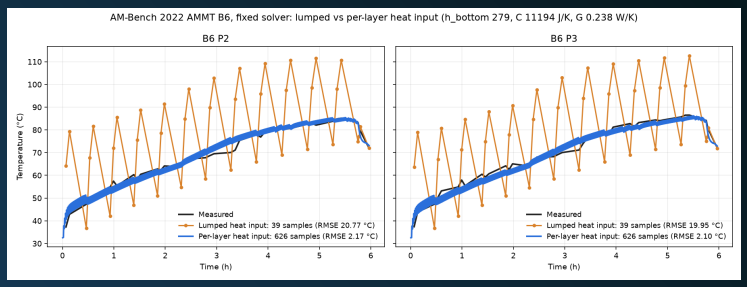
PROTOCOL · VALIDATED OPERATING DOMAIN

- Material & process envelopes
- Design-feature coverage
- Machine-family equivalence
- Uncertainty & out-of-domain rules

Certification controls the evidence, model lineage and validated limits — while configurations evolve freely within them.

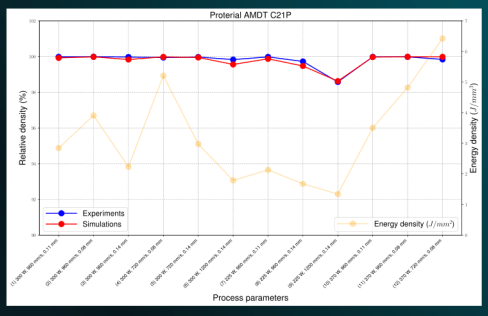
Quantities involved in calibration

1) Thermocouple temperature below baseplate



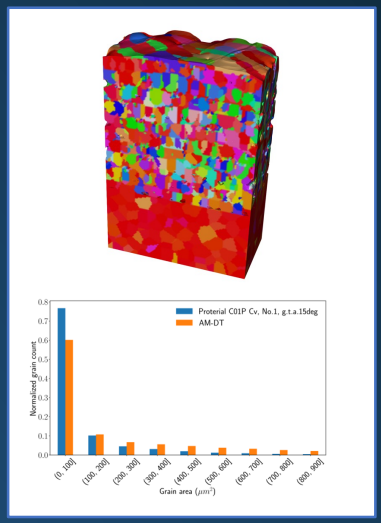
Example

2) Porosity



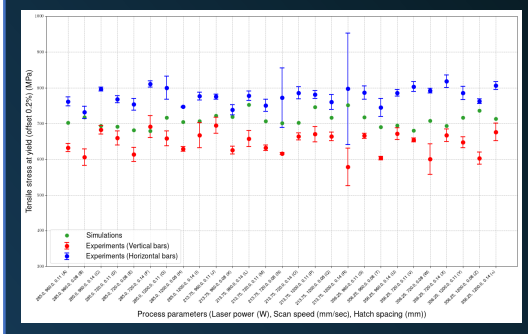
Example

3) Microstructure



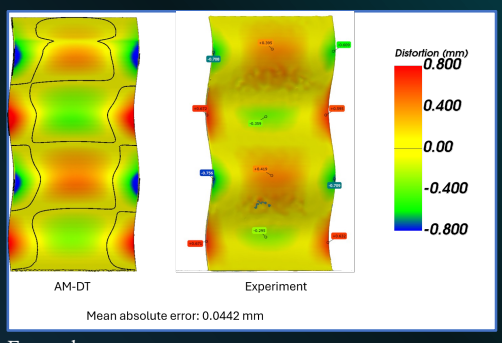
Example

4) Mechanical properties



Example

5) Distortion

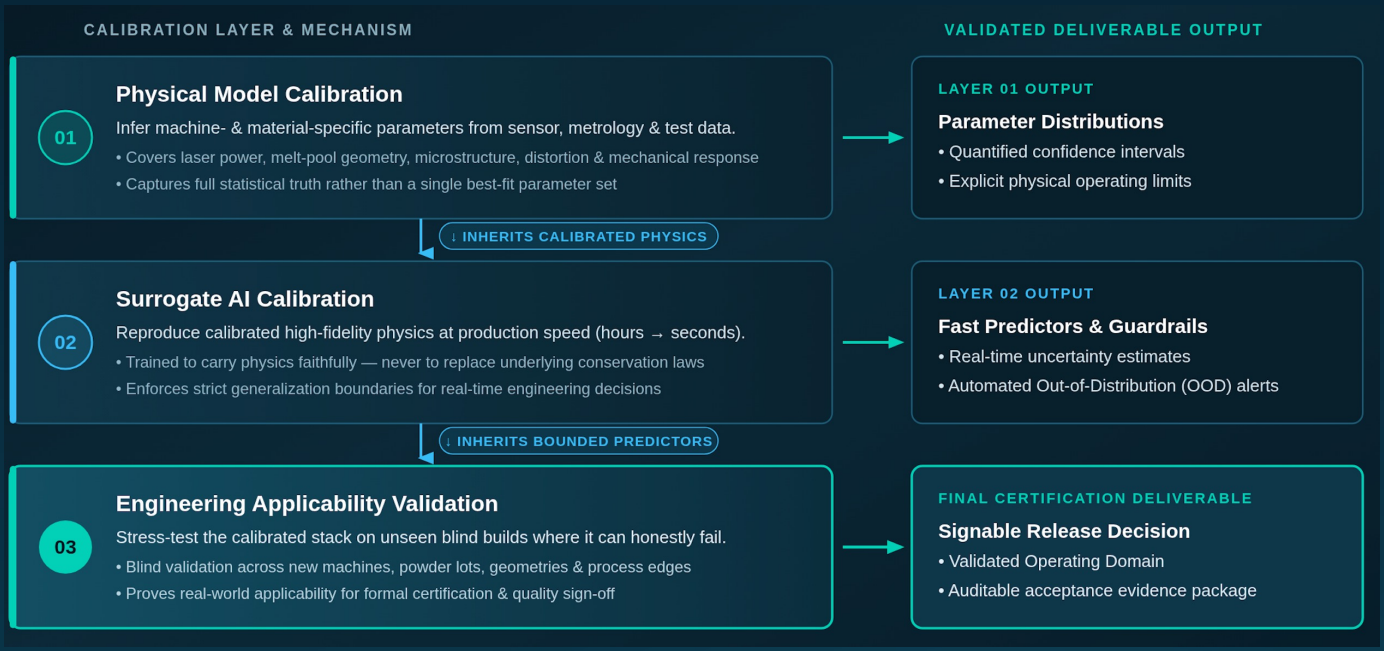


Example

SECTION 02 · THE CALIBRATION PROTOCOL

Three Calibration Layers Connect Evidence to Decisions

The protocol rests on three sequential calibration layers. Each layer consumes the validated output of the one before it, so that confidence is inherited, not asserted — from raw physical evidence, through accelerated prediction, to an engineering decision a quality organization can sign.



The calibrated stack is tested where it can honestly fail: **blind builds** across machines, powder lots, geometries and process-window boundaries — evidence the model has never seen. Only surviving this gauntlet produces the deliverables that matter to a certification conversation: a **validated domain, acceptance evidence and a release decision**.

Calibration layers connect physical evidence to qualification decisions

01	**PHYSICAL MODEL CALIBRATION** Infer machine- and material-specific parameters using sensor, metrology and test evidence.	Output Parameter distributions, confidence intervals and physical limits
02	**SURROGATE AI CALIBRATION** Reproduce calibrated high-fidelity physics at engineering speed with explicit generalization limits.	Output Fast predictors, uncertainty estimates and Out-of-Distribution detection
03	**ENGINEERING APPLICABILITY VALIDATION** Test blind builds across machines, powder lots, geometries and process-window boundaries.	Output Validated domain, acceptance evidence and release decision

SECTION 02 · THE CALIBRATION PROTOCOL

The Protocol Converts Every Build into a Controlled Evidence Workflow

Eight steps, two movements. The first movement — **Calibrate** — builds the evidential foundation; the second — **Validate · Release · Learn** — turns that foundation into a living qualification asset. Nothing here is a one-time exercise: each pass through the loop tightens the domain and appreciates the asset.

CALIBRATE

01 **Define the domain and the configuration fingerprint.**
Scope where predictions must hold, and register the exact machine–powder–build–model identity.

02 **Ingest build records and complete data QA(Quality Assurance).**
Synchronize, register and quality-flag every machine, sensing and inspection stream into immutable raw evidence.

03 **Run baseline, DOE (Design of Experiments) and boundary builds.**
Establish nominal behaviour, probe sensitivities, and deliberately walk the process to its failure edges.

04 **Calibrate physics across all scales.**
Infer parameters sequentially from machine energy input through melt pool, microstructure and part performance.

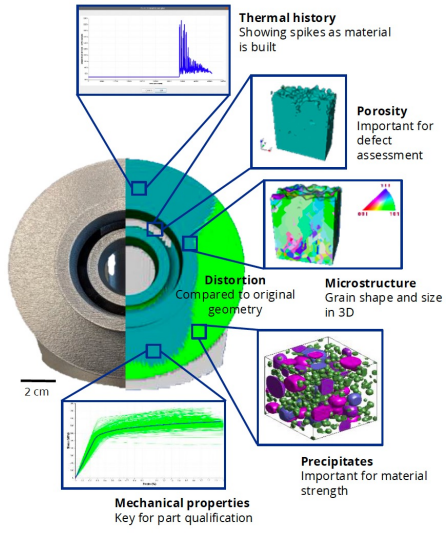
VALIDATE · RELEASE · LEARN

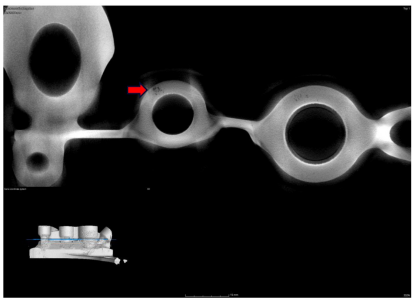
05 **Calibrate and gate the Surrogate AI.**
Reproduce calibrated physics at speed, then pass release gates: constraint enforcement, uncertainty, OOD detection.

06 **Validate on blind, independent builds.**
New plates, powder lots, geometries or machines — evidence outside the calibration set decides applicability.

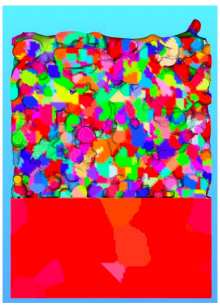
07 **Release a versioned calibration package.**
Fingerprint, posteriors, model versions, validation report, domain limits and hash — sealed and traceable.

08 **Apply delta qualification and continuous learning.**
Re-test what a change actually touches; feed every outcome back to tighten the next prediction.





Z = 50.5 mm
Element 2949774



Porosity = 2.95408%

Example: SynaCore AM-DT Porosity calibration

A Calibration Domain Defines Where Predictions Remain Valid

THE DOMAIN ENVELOPE

The calibration domain is the explicit envelope within which predictions carry their validated confidence. It spans six dimensions: **machine**: family, optics, lasers and condition; **materia** : grade, powder specification and reuse history; **process**: power, speed, layer thickness and preheat; **design**: walls, overhangs, channels and heat accumulation; **sensing**: sensor type, location, sampling rate and uncertainty; and **post-processing** : heat treatment and finishing route.

The envelope is not a cage; it is a contract. Inside it, predictions are qualification-grade. Step outside it: a new powder lot beyond its registered reuse history, a geometry feature beyond validated coverage, and the protocol's rule is unconditional: **predictions outside the envelope trigger additional simulation or testing**. The system's integrity lies precisely in knowing when not to answer.

TRACEABLE CONFIGURATION FINGERPRINT

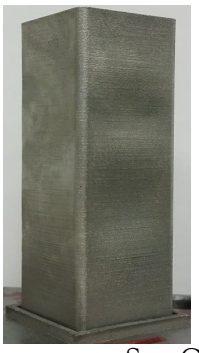
Every qualification statement is anchored to a four-part digital genealogy, so that any claim can be traced back to the exact evidence and model version that produced it:

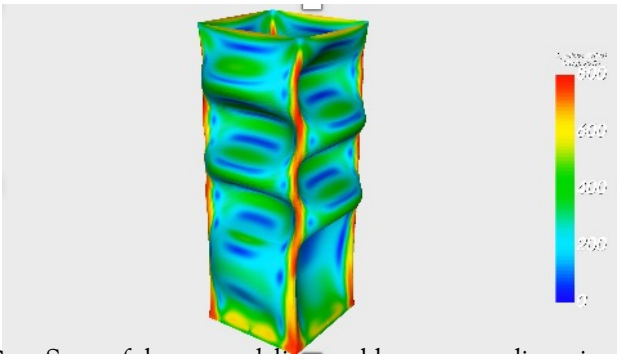
- **Machine ID** — equipment state and sensor configuration at build time
- **Powder Lot ID** — chemistry, physical properties and reuse history
- **Build ID** — design, process, sensing, inspection and outcome
- **Model Version ID** — parameters, surrogate, validation and domain limits

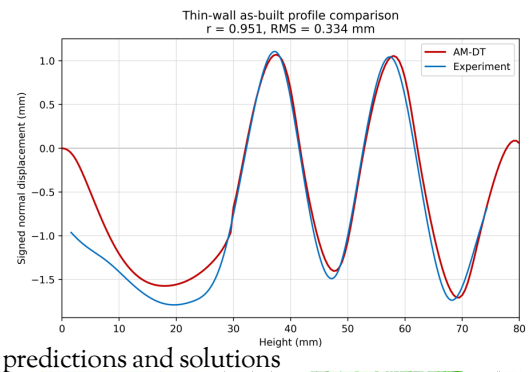
Together, domain and genealogy answer the two questions any certification society will ask first: *"here does this prediction apply?* and *Exactly what produced it?* A qualification claim that cannot answer both is an opinion. One that can is evidence — reproducible, auditable, and portable across the life of the part.

This is the protocol's central move: **Digital Twin plus surrogate AI shifts the unit of control from a frozen combination to a bounded, evidence-backed domain.** Within the domain, a parameter change is no longer an act of regulatory defiance; it is a computable event whose impact the calibrated twin evaluates in advance. Outside the domain, the system does not bluff — out-of-domain rules mandate additional simulation or testing before any qualification statement is made.

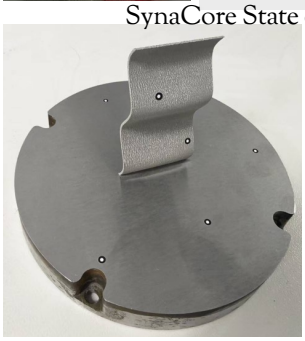
Equally deliberate is the word **manufacturer-led**. The raw data never leaves the manufacturer's hands; the process knowledge, the calibrated parameters and every model-release decision remain under manufacturer control. Calibration is an asset that appreciates with every build.

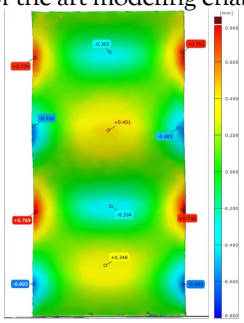


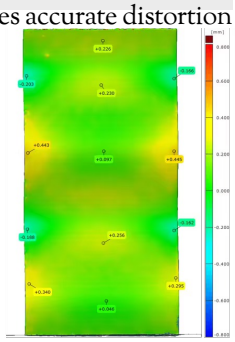


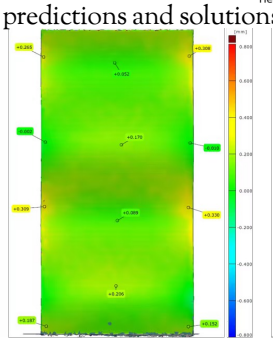


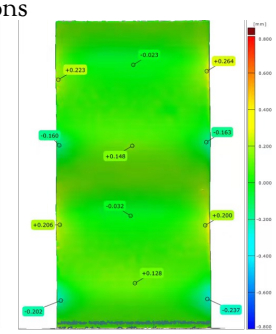
SynaCore State of the art modeling enables accurate distortion predictions and solutions











Default Parameters | Precompensated-1 | Precompensated-2 | Precompensated-3

SECTION 02 · THE CALIBRATION PROTOCOL

Disciplined Data, Deliberate Experiments

DATA SPECIFICATION

Calibration is only as strong as the build record beneath it. The protocol specifies five synchronized data families: machine & process — power, scan path, layer time, oxygen, gas flow, preheat, alarms; powder & material — chemistry, size distribution, morphology, flow, density, recycling history; in-situ sensing — melt-pool signals, coaxial and off-axis layer images, infrared thermography, acoustics, eddy current arrays, and recoating anomalies; post-build metrology — tiered verification combining rapid, non-destructive CWT-enhanced immersion ultrasound (UT) for high-throughput volumetric porosity and microstructural scattering mapping, anchored by targeted X-ray CT, metallography, and SEM/EBSD for distortion, residual stress, and mechanical properties; and outcome & data quality — success, failure, defects, missing data, noise, and sensor status.

All streams pass through one mandatory registration pipeline — time synchronization (FPGA) → spatial orthorectification (mm) → physical-signal calibration (temperature & conductivity & plume/gas-flow attenuation compensation) → layer/scan alignment → QA flags → immutable raw record. Cleaning, labelling, and feature extraction create derived versions; they never overwrite the original evidence.

CALIBRATION EXPERIMENT DESIGN

Calibration experiments must span nominal performance *and* failure boundaries; a model that has only seen success cannot know where success ends. Four build classes serve distinct evidential roles:

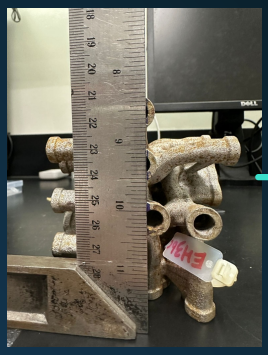
Baseline builds — reference coupons and representative geometry establish machine and material baselines.

Parameter DOE — controlled perturbations reveal sensitivities and interactions within the process window.

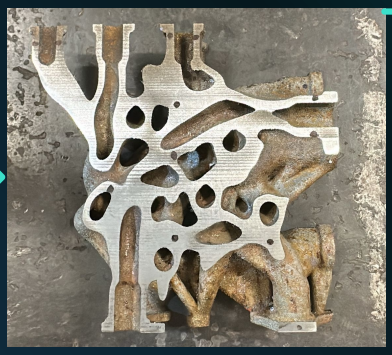
Boundary & failure builds — lack of fusion, keyholing, overheating and distortion define where the process fails.

Blind validation builds — new plates, powder lots, geometries or machines test transfer beyond the calibration set.

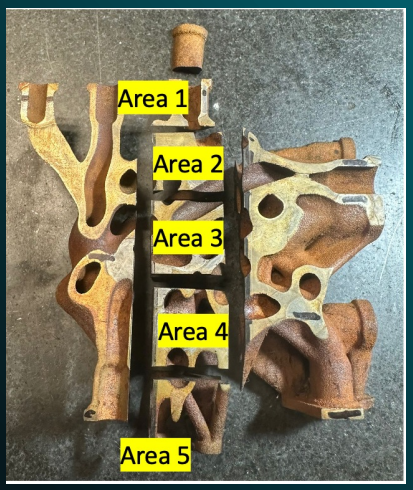




Original sample before wire-cutting



Wire-cut cross-section

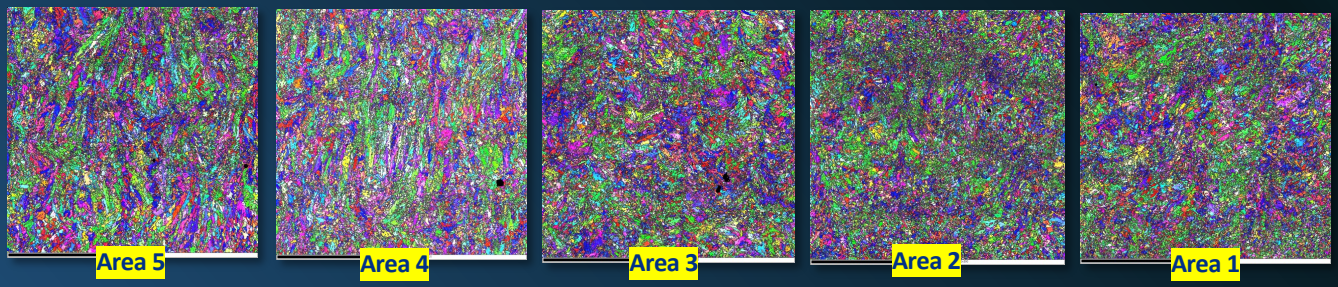


Areas for EBSD analysis

Experimental work by

ADDITIVE INNOVATION CENTRE
Supported by NAMIC

Experimental verification: Example



SECTION 02 · THE CALIBRATION PROTOCOL

Sensor Spatial Calibration: Anchoring Pixels to Physical Truth

Raw in-situ optical and thermal images suffer from oblique mounting angles, perspective distortion, and non-linear lens aberrations. Before sensor data can calibrate physics models or feed surrogate AI, **every pixel must be mathematically anchored to the build plate's physical millimetre coordinate system**.

THREE-STAGE SPATIAL REGISTRATION PIPELINE

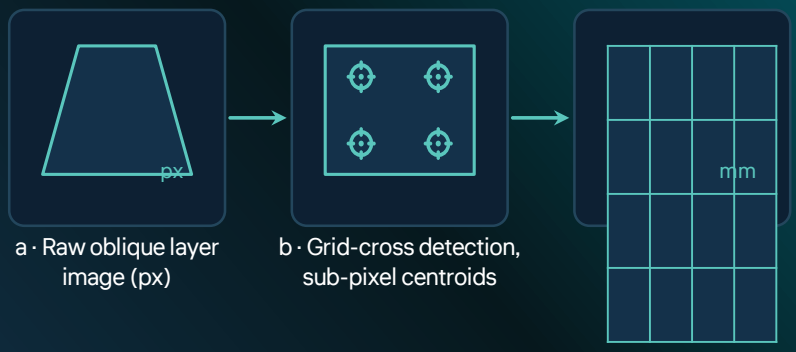
01 **Feature Extraction & Masking**
Automated masking, median filtering and thresholding isolate the active build plate; calibration artefact markers (reference grid crosses) are detected at **sub-pixel accuracy** to establish raw sensor coordinates (px).

02 **Non-Linear Distortion Modeling (Thin-Plate Spline)**
Rigid pinhole assumptions fail under chamber refraction and lens warping; a non-parametric **Thin-Plate Spline (TPS)** model maps true physical reference grids (mm) to distorted image coordinates (px).

03 **Offline Warp-Field Generation & Real-Time Remapping**
Static warp fields are computed offline over a standardized millimetre sampling grid; during live builds, lightweight real-time remapping yields orthorectified, metric-accurate layer maps with **zero latency penalty**.

> *"Uncalibrated images are pictures; spatially calibrated images are metrology instruments."*

FROM PIXELS TO MILLIMETRES



a · Raw oblique layer image (px)

b · Grid-cross detection, sub-pixel centroids

c · Orthorectified millimetre grid overlay

CORE METROLOGY OUTCOMES

Metrology-Grade Defect Localization

Turns "a dark spot exists" into **"a 0.4 mm recoater streak at (x, y, z)"** — quantitative evidence comparable against CAD tolerances and post-build CT scans.

Cross-Machine Geometric Normalization

Removes camera mounting and optical variations across OEM machines, projecting raw pixels into a **unified millimetre frame** within the SynaCore Domain Envelope.

Auditable Spatial Lineage in DT-DPP

Calibration metadata, TPS residual error maps and uncertainty bounds are embedded in the **Traceable Configuration Fingerprint** — every pixel's location is mathematically bounded.

SECTION 02 · THE CALIBRATION PROTOCOL

Spatio-Temporal Binding: Unlocking Cost-Effective Off-Axis Sensing

While coaxial sensors require expensive optical hardware modifications, most industrial AM fleets rely on cost-effective off-axis sensors — overhead visible cameras, infrared imagers, and optical tomography. Off-axis sensing captures full-plate thermal accumulation, cooling rates, and spatter trajectories, but shifts the engineering challenge from simple time-stamping to **dual spatio-temporal binding**.

BRIDGING OFF-AXIS STREAMS TO THE 3D TOOLPATH FRAME

01 **Hardware-Synchronized Temporal Alignment (Δt Compensation)**
Off-axis frames and coaxial signals are synchronized to the laser controller via **FPGA hardware triggers**; microsecond latency Δt is compensated, locking each frame to its laser scan vector $(X(t), Y(t), Z)$.

02 **Dynamic Melt-Pool & Cooling-Wake Tracking**
Orthorectified (TPS) and time-locked to the toolpath, the twin projects dynamic tracking windows onto calibrated frames—normalizing radiance signals against local gas-flow vectors and scan-direction plume attenuation before separating melt-pool intensity, trailing cooling rates, and spatter landing zones.

03 **Unified 3D Voxel Data Cube Construction**
Multi-modal layer images, thermal histories, and laser parameters are stacked layer-by-layer into a single 3D Voxel Data Cube—an immutable, cross-validated evidence stream for sequential physics calibration.

> *"Coaxial optics capture the spark; calibrated off-axis sensing captures the whole thermal story — at a fraction of the hardware cost."*

DUAL BINDING · SPACE + TIME



a · Off-axis thermal & optical streams

b · FPGA clock sync + toolpath tracking window

c · 3D multi-modal voxel data cube

STRATEGIC VALUE FOR PRE-QUALIFICATION & FLEET SCALING

Hardware-Agnostic Sensor Democratization

Retrofit existing machines with **standard off-axis cameras** — no costly proprietary coaxial upgrades — and still produce certification-grade, toolpath-aligned evidence.

Full Thermal History Beyond the Spark

Captures part-scale heat accumulation and post-exposure cooling rates — physical drivers of **grain microstructure and residual stress** that narrow-field coaxial sensors cannot observe.

Cross-Modal False-Positive Elimination

Surface anomalies from layer-wise imaging are cross-checked against flow-compensated thermal histories at the same ((X, Y, Z) coordinate, so benign reflections and directional plume fluctuations no longer trigger false rejects.

SECTION 02 · THE CALIBRATION PROTOCOL

Multi-Scale Calibration, and AI That Is Governed Like Evidence

SEQUENTIAL CALIBRATION ACROSS SCALES

Physics is calibrated sequentially so that fidelity is preserved across scales rather than smeared across them. Each scale contributes its own observations before the next is touched:

01 · Machine & energy input — power, spot, scan delay, thermal boundary response.

02 · Melt pool & defects — pool geometry, cooling rate, stability, porosity, spatter.

03 · Microstructure & phases — grain size and orientation, phases, precipitate evolution.

04 · Part performance — distortion, residual stress, heat-treatment response, mechanical properties.

Failed builds are high-value boundary evidence.

A failed build maps the edge of the possible — precisely where qualification needs the model to be right. The protocol separates genuine manufacturing failures from sensor faults, missing data and operating errors before ingestion, so that failure teaches the physics rather than corrupting it. In this framework, nothing printed is wasted: every outcome sharpens the boundary on which safe qualification depends.

Calibration output

Parameter posteriors, confidence intervals, correlations and applicability conditions — never a single best-fit parameter set presented as truth.

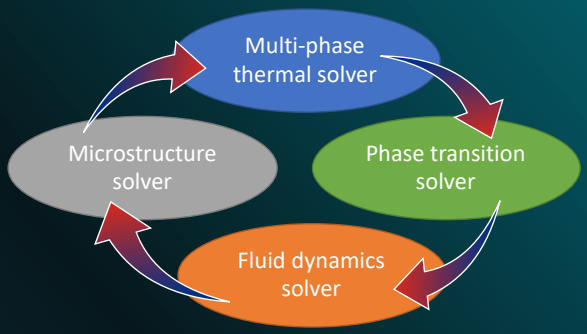
Out-of-domain path: additional simulation or testing is required; automatic qualification is disabled.

SURROGATE AI GOVERNANCE

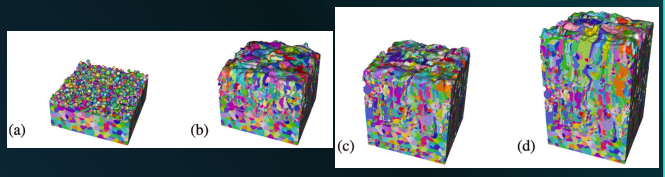
Surrogate AI requires its own calibration and release gates, because a fast wrong answer is worse than a slow right one. The surrogate learns from three sources — calibrated high-fidelity simulations, experimental observations and historical build records — and in return must pass five non-negotiable gates before release:

01 Split datasets by complete Build ID — no leakage
02 Enforce physical constraints on every prediction
03 Quantify predictive uncertainty, not just accuracy
04 Detect out-of-domain inputs before answering
05 Report surrogate and physics errors separately

SynaCore Integrated model for microstructure and defects prediction in 3D



- Each solver was reviewed to maximize speed
- Implemented using Message-Passing Interface (MPI)
- Code scales from workstations to supercomputers



R. Laskowski *et al.*, Additive Manuf. **60**,103266 (2022)
Wei *et al.*, Additive Manuf. **54**, 102779 (2022)

These two disciplines — sequential physics calibration and governed AI — are what make the twin's speed trustworthy. The surrogate can predict at engineering pace *because* the physics beneath it was calibrated scale by scale, and it can be trusted in certification conversations *because* its uncertainty, its error budget and its domain boundaries are disclosed by design rather than discovered by accident.

SECTION 02 · THE CALIBRATION PROTOCOL

Design-Intent Alignment: Translating MBD Tolerances into Local Acceptance Thresholds

A calibrated prediction is only actionable when measured against the part's true engineering intent. Standard AM workflows convert CAD designs into STL meshes — stripping away critical Product Manufacturing Information (PMI) such as geometric tolerances, surface roughness, and fatigue-critical zones. SynaCore AM-DT **bypasses the STL bottleneck**, mapping Model-Based Definition (MBD) requirements directly onto the simulation mesh as spatially resolved acceptance thresholds.

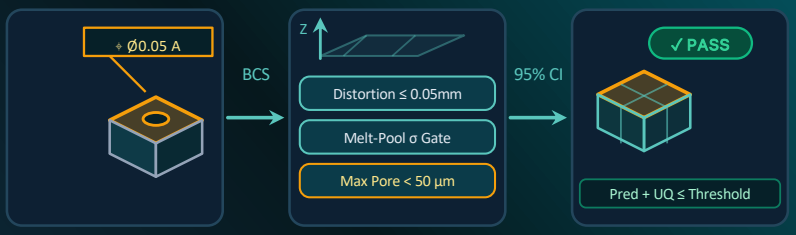
01 **Lossless PMI Extraction & BCS Registration**
Parse native CAD or STEP AP242 files to extract GD&T tolerances, surface finish specs R_a and critical-zone tags; build-layout matrices map each annotated surface into the **Build-Plate Coordinate System (BCS)**.

02 **Cross-Physics Threshold Mapping**
Dimensional tolerances govern allowable distortion and residual stress; surface-roughness specs tighten contour **melt-pool stability**; fatigue-critical zones enforce strict limits on maximum pore and grain size.

03 **Uncertainty-Bounded Pass/Fail Gating**
A local feature passes only when $Predicted + Uncertainty\ (95\%\ CI) \leq MBD\ Threshold$; out-of-tolerance zones automatically trigger **geometric pre-compensation or toolpath adaptation**.

"STL files describe a shape; MBD defines a contract. Anchoring tolerances to the simulation mesh turns design intent into automated qualification gates."

FROM MBD TO LOCAL GATES



a · MBD / STEP AP242 (GD&T + critical zones) b · BCS spatial binding & physics translation c · 3D mesh with local acceptance envelopes

CORE VALUE FOR PRE-QUALIFICATION & CERTIFICATION

Eliminating False Rejects via Zoned Criteria

Distinguishes tight-tolerance mating surfaces from non-critical structural regions — benign anomalies in low-stress areas no longer trigger **unnecessary build aborts or scrap**.

Automated Pre-Build Geometry Compensation

Identifies localized distortion breaches against GD&T limits **before printing begins**, enabling closed-loop inverse pre-compensation to bring the virtual part inside tolerance.

Feature-Level Auditability in DT-DPP

Local MBD thresholds, predicted values, in-situ measurements and safety margins are recorded in the **Digital Birth Record** — feature-by-feature proof of compliance.

SECTION 02 · THE CALIBRATION PROTOCOL

From Anomaly Detection to Fitness-for-Service: Defect-Tolerant Fatigue Assessment

Detecting an anomaly in-situ is not the same as knowing whether a part will survive in service. Standalone vision AI flags pores or recoater streaks as raw pixel alerts, often triggering conservative scrap. SynaCore AM-DT bridges this gap by mapping multi-label defect segmentation directly onto the 3D physics mesh — **coupling real defect geometries with residual stress and fracture mechanics** to predict local fatigue life.

01 3D Voxel Mapping & Remelting Correction

Stack calibrated 2D multi-label defect maps into the BCS, applying thermal solver displacements and melt-pool depth to **filter out shallow anomalies healed by subsequent remelting**.

02 Physics-Equivalent Constitutive Degradation

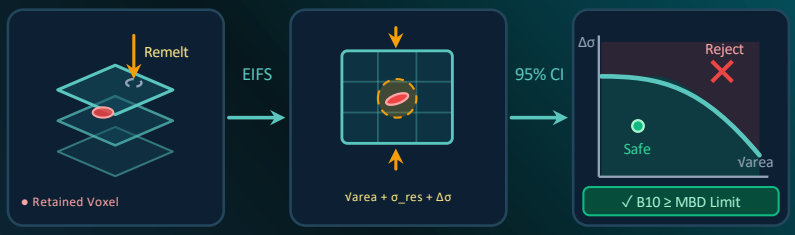
Convert internal pores into **Equivalent Initial Flaw Sizes** $\sqrt{area}$, translate recoater damage into local stress concentrations K_t, and link thermal anomalies to grain-scale yield updates.

03 Residual-Stress-Coupled Fatigue Gating

Superimpose service loads onto as-built residual stresses within a **Kitagawa-Takahashi fracture framework**, gating release where 95% lower-confidence fatigue life B_{10} meets local MBD thresholds.

> *"Pixel-level alerts tell you what went wrong on a layer; physics-coupled fracture models tell you whether the part is fit to fly."*

FROM ANOMALY MAPS TO FATIGUE LIFE



a · 3D defect voxel field (remelting-filtered) b · Fracture equivalence (EIFS √area + σ_res) c · Kitagawa-Takahashi gating (B10 ≥ MBD)

CORE VALUE FOR PRE-QUALIFICATION & DISPOSITIONING

Preventing Costly False Scrap

Separates benign anomalies in low-stress zones from **life-limiting defects in fatigue-critical regions**, salvaging high-value builds that pixel-only alerts would reject.

Targeted Post-Build NDE Routing

Directs expensive offline CT scans exclusively to suspect voxels breaching local B_{10} life margins — replacing **blanket inspection with risk-informed verification**.

Service-Ready Digital Birth Record

Mapped defect sizes, residual stress states and probabilistic fatigue margins are archived inside the **DT-DPP** — proving fitness-for-service to regulators before deployment.

SECTION 02 · THE CALIBRATION PROTOCOL

Validation, Assetization and Delta Qualification

THE BLIND VALIDATION GATE

Every build — success or failure — faces one honest examiner: blind validation on evidence the model has never seen. Five metrics decide whether the calibrated stack may be released, and a weakness in any one of them sends the model back rather than the part forward:

· Prediction error across scales
· Prediction-interval coverage
· Critical-defect false negatives
· Transfer across builds, lots and machines
· Boundary stability and conservatism

FOUR REUSABLE ASSETS

01 · Raw evidence — traceable process, sensing and inspection data
02 · Physical knowledge — parameters, process windows, failure limits
03 · Model assets — physics, surrogate and validated applicability
04 · Qualification evidence — equivalence and uncertainty records for reuse

Step back and the economics come into focus. Calibration turns every build into a manufacturer-owned asset whose value compounds; delta qualification turns change from a requalification threat into a routine engineering event; and the digital birth record turns each part's certification from a post-hoc verdict into an a priori property — earned before the laser ever fires.

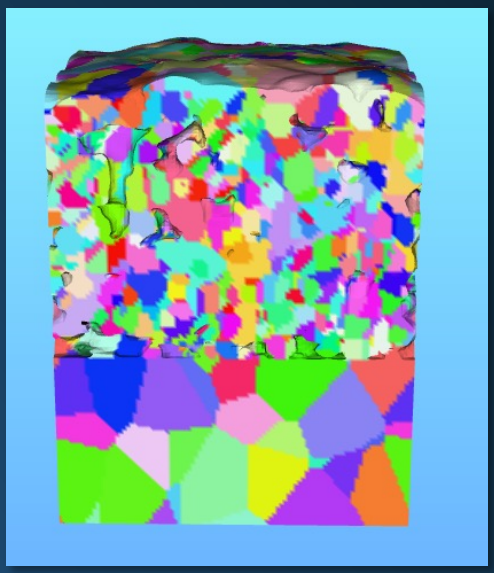
DELTA QUALIFICATION IN PRACTICE

Release is not the end of calibration but its dividend. The versioned release package seals everything a qualification claim needs — configuration fingerprint, parameter posterior, physics and surrogate versions, validation report, domain limits, restrictions and model hash — so that any later question has a permanent address.
When something changes — a powder lot, a parameter refinement, a machine overhaul — delta qualification evaluates the change inside the calibrated domain and re-tests only what the change actually touches. By pairing digital twin predictions with rapid, low-cost confirmatory NDE such as wavelet-processed immersion ultrasound, manufacturers validate volumetric integrity in minutes rather than weeks of costly CT scanning. Evidence is not weakened by repetition avoided; it is strengthened by irrelevance removed. This is how L2/L3-style requalification triggers shrink in frequency and scope without a gram of rigour being surrendered.

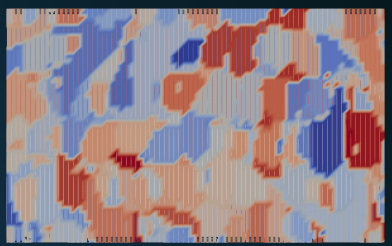
THE PRE-BUILD QUALIFICATION OUTPUT

A traceable **digital birth record** for every part: predicted performance, qualified process window, quantified uncertainty, full model lineage — and the specific confirmatory evidence still required. Controlled domains, continuous calibration and independent validation let qualification evolve with manufacturing knowledge itself.

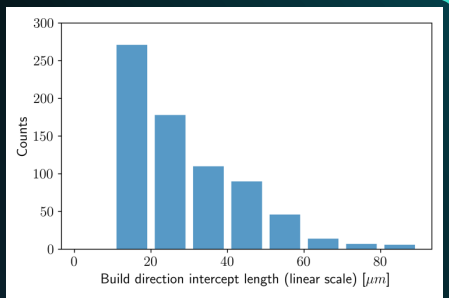
SynaCore Micostructure Validation



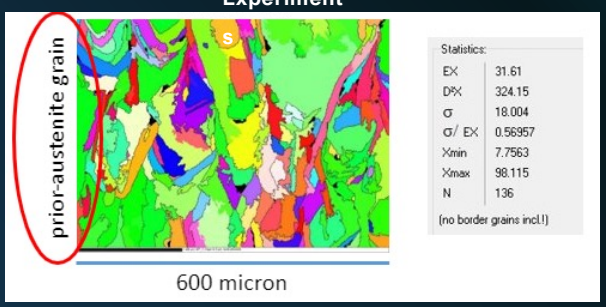
3D as-built microstructure



Implementation of linear intercept method to measure grain size on our digital microstructure



Experiment



AI vs Digital Twin + AI

Calibration Changes the Claim

SECTION 03

CAPABILITY DIMENSION	Pure Data-Driven AI Black-Box Vision / kNN	Conventional Thermal Sim Nominal Part-Scale FEA	SynaCore AM-DT Calibrated Multi-Scale Physics + AI
1. Physical Foundation	✕ **No physical model** Statistical image/CT pattern fit	△ **Single-scale heat only** Melt-pool & powder physics absent	✓ **Full multi-scale coupling** Powder → melt pool → grain → part
2. Role of Surrogate AI	✕ **Direct final predictor** kNN/vision decides without physics	— **No AI acceleration** Slow unaccelerated simulation	✓ **Physics-carrying accelerator** Full-part fidelity at production speed
3. Prediction Output	✕ **Raw pixel anomaly alerts** No physical or mechanical meaning	△ **Intermediate metrics only** Porosity, hardness, grain size	✓ **Final service performance** Strength, fatigue life + audit proof
4. Boundary Coverage	✕ **Contour blind spot** Excludes edges; misses surface pores	△ **Nominal heat transfer** Lacks live sensor feedback	✓ **100% contour & infill coverage** Toolpath-aware near-surface physics
5. New Part Generalization	✕ **High overfit fragility** Error spikes on unseen geometries	△ **Partial transferability** Retuned per new part family	✓ **Domain-envelope transfer** Blind-validated on unseen builds
6. Uncertainty Quantification	✕ **No confidence bounds** Point predictions only	△ **Deterministic single value** No statistical confidence	✓ **Voxel-level** Confidence Auditable uncertainty pedigree
7. Certification Evidence	✕ **Post-hoc alerts only** Not auditable for qualification	△ **Engineering reference** No acceptance evidence chain	✓ **Signable release asset** Pre-build, audit-ready evidence

SECTION 03 · A DIFFERENT KIND OF PHYSICS + AI

Not All "Physics + AI" Is Equal — Calibration Changes the Claim

As model-based qualification gains attention, physics-informed AI has become a label claimed by very different architectures. A recent and representative academic approach couples a part-scale thermal simulation with machine learning for rapid quality assessment — a genuine step forward, and a useful foil. Measured against the demands of pre-qualification, seven dimensions separate a physics-AI assessment tool from a calibrated, self-evolving certification asset.

Capability / Dimension	Pure Data-Driven / Black-Box AI	Conventional Thermal Sim	SynaCore AM-DT (Physics AI enhanced)
Physical foundation	No physical model at all — statistical patterns learned from labeled images and CT data	Single-scale (part-level heat diffusion); melt-pool / powder physics absent	**Multi-scale coupling** (powder – melt pool – grain – part), with physics intrinsic to the model
Role of surrogate AI	The network itself is the final predictor (kNN / vision model decides directly)	None — simulation runs without learning acceleration	**Accelerator** enabling multi-scale, high-fidelity physical simulation for full-scale parts
Prediction output	Raw pixel-level anomaly alerts, without physical quantification	Intermediate quality metrics (porosity, hardness, grain size)	**Final service performance** (strength, fatigue, heat-treatment response) + certification evidence
SENSING & DEFECT DETECTION			
Part Boundary & Contour Coverage	**Blind spot:** often excludes outer contours to avoid false alarms from abrupt powder-solid thermal shifts	Nominal heat transfer only; lacks real sensor feedback	**Full boundary coverage:** toolpath-aware physics resolves contour-vs-infill thermal boundaries, capturing critical near-surface pores
Unseen Geometry Generalization	**High overfit risk:** false-positive and false-negative rates spike on new geometries or scan vectors	Generalizes well, but slow and uncalibrated to live machine drift	**Physics-anchored generalization:** conservation laws + directional plume compensation ensure stable accuracy on unseen parts
Model form	Static after training; degrades with machine and process drift	Static nominal model, uncalibrated to live machine drift	**Self-evolving**, continuously calibrated with real data, forming proprietary digital assets
Certification logic	Post-hoc (in-situ) rapid assessment, replacing part of inspection	Offline design exploration; no live certification claim	**Pre-build predictive certification**, generating a "digital birth certificate"

WHY PURE DATA-DRIVEN ANOMALY DETECTION HITS A CEILING

The Boundary Blind Spot

Conventional tools flag high-variance energy shifts against post-build CT. Because thermal boundary conditions shift abruptly at part contours, statistical models exclude boundary regions to suppress false alarms — leaving the near-surface pores that govern fatigue uninspected.

Fragility on Unseen Geometries

Without embedded conservation laws and directional gas-flow plume compensation, empirical networks overfit to training coupons. Transferred to unseen geometries or altered scan vectors, false-positive and false-negative rates spike unpredictably.

The SynaCore Advantage

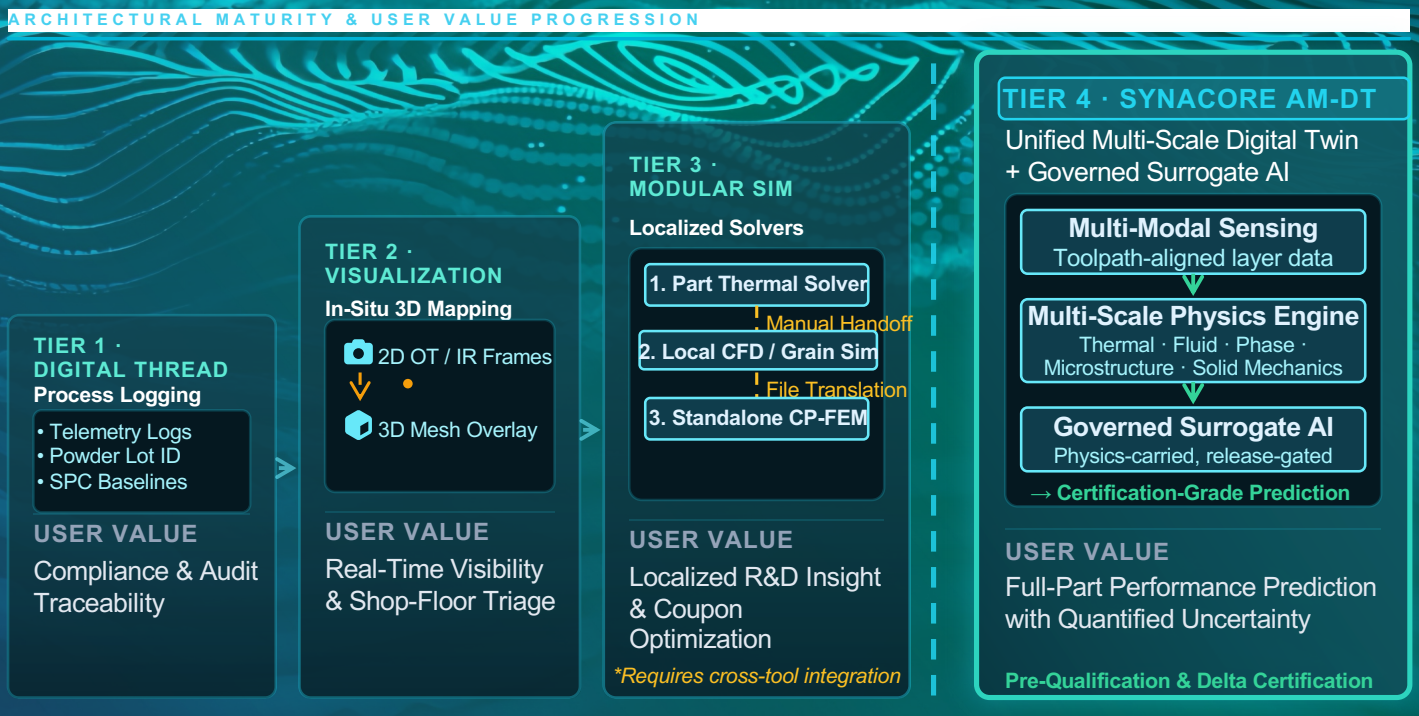
Anchoring multi-modal sensing to toolpath-aware, first-principles physics, SynaCore evaluates signals against **local physical expectations** rather than raw variance — delivering low-false-alarm defect localization across unseen geometries, including critical part boundaries.

A static physics-AI model can accelerate assessment after the build — but it **cannot certify before it**. A calibrated, self-evolving twin carries **auditable lineage, quantified uncertainty and a defined domain** on every prediction: precisely what a digital birth certificate must contain.

The Technical Advantage of SynaCore AM-DT

Bridging the Generational Divide

SECTION 04



SECTION 04 · THE TECHNICAL ADVANTAGE OF SYNACORE AM-DT

From Fragmented Workflows to Machine-Customized Digital Twins

DELIVERING END-TO-END QUALIFICATION VALUE

Qualifying a complex flight component today means orchestrating a multi-step relay across disconnected tools — part-scale thermal simulation, manual thermal-history segmentation, and boundary conditions shuttled between separate melt-pool, solidification and crystal-plasticity packages. SynaCore AM-DT bridges this generational divide: one cohesive platform that turns virtual intelligence into direct production and certification value.

5.1 · THE EVOLUTION OF DIGITAL TWIN CAPABILITIES MATCHING ARCHITECTURE TO USER VALUE

DIGITAL TWIN PARADIGM	PRIMARY ARCHITECTURE	CORE VALUE DELIVERED TO THE USER	ROLE IN THE QUALIFICATION JOURNEY
Tier 1 · Digital Thread Process Logging	Telemetry databases & build lineage tracking	Standardized compliance logging, auditability and parameter baseline checks	Establishes auditable manufacturing records
Tier 2 · Process Visualization In-Situ Monitoring & 3D View	2D-to-3D sensor mapping & anomaly dashboards	Immediate visual feedback and layer-wise anomaly screening	Supports rapid in-process shop-floor triage
Tier 3 · Modular Simulation Localized Solvers	Standalone thermal, CFD, or grain / CP-FEM solvers	Deep localized physical insight for R&D and coupon optimization	Guides process exploration on isolated sub-volumes
Tier 4 · SynaCore AM-DT Unified Multi-Scale DT + Surrogate AI	Natively coupled multi-modal sensing + multi-scale physics + Surrogate AI	Zero-handoff, full-part performance prediction with quantified uncertainty	**Unlocks pre-build qualification & Delta Certification**

SECTION 04 · THE TECHNICAL ADVANTAGE OF SYNACORE AM-DT

Protecting Engineering Investments Across Geometries, Fleets and Machines

GENERALIZATION · ROBUSTNESS · MACHINE-SPECIFIC CUSTOMIZATION

5.2 · GENERALIZATION AND ROBUSTNESS

Physics-Anchored Generalization

Surrogate AI anchored to calibrated conservation laws evaluates unseen CAD topologies — from thin-walled heat exchangers to load-bearing brackets — without repeating costly trial builds.

Toolpath-Aware Boundary Precision

Sensor streams co-registered to the laser toolpath frame, with directional gas-flow plume compensation, resolve near-surface physics at contours and down-skin regions — sparing false-positive build aborts.

Domain Envelopes & OOD Guardrails

Bayesian parameter posteriors and automated Out-of-Distribution detection quantify uncertainty at every voxel and alert engineers whenever a change steps outside the validated Domain Envelope.

5.3 · MACHINE-SPECIFIC CUSTOMIZATION UNLOCKING CONTROLLED FATIGUE QUALIFICATION

AM fatigue life is dictated by the extreme-value distribution of defects — and defect formation is intensely machine-dependent. Generic tools apply idealized heat sources that treat all printers alike; SynaCore customizes the twin to each machine's exact physical signature.

01 **Mirroring Exact Hardware Behavior**
The Manufacturer-Led Calibration Protocol calibrates energy coupling, melt-pool hydrodynamics and sensor transfer functions to match how a specific machine model operates in production.

02 **From Defect Physics to Controlled Fatigue Gating**
Reflecting the machine's true physical signature, the twin predicts 3D remelting-filtered defect distributions and couples Equivalent Initial Flaw Sizes ($\sqrt{area}$) with local residual stresses inside a Kitagawa-Takahashi fracture framework.

03 **A Proprietary Qualification Asset**
Anchoring fatigue predictions to calibrated, machine-specific physics rather than generic literature curves gives manufacturers a controlled, repeatable pathway to pre-qualify fatigue-critical components — turning equipment behavior into an auditable engineering advantage.

Case Studies

Customer Value Centric

SECTION 05

Pre-qualifying Complex Heat Exchangers: In-Situ Metrology for Unreachable Geometries

HIGH-VALUE USE CASE · INTERNAL NON-INSPECTABLE FEATURES



Metal AM heat-exchanger core with corrugated internal micro-channels — features unreachable by CMM or optical metrology after the build.

THE CERTIFICATION BOTTLENECK

Next-generation aerospace heat exchangers, conformal cooling dies and RF waveguides rely on intricate internal micro-channels and ultra-thin corrugated fins. Once printed, these features are physically unreachable by CMM or optical scanners, while dense metallic walls attenuate industrial X-ray CT resolution and drive prohibitive inspection costs.

PRE-QUALIFICATION OUTCOME

Every internal channel receives a metrically traceable, layer-verified geometric and functional birth record inside the DT-DPP — eliminating destructive sectioning, reducing post-build CT dependency, and giving regulators auditable proof of internal structural integrity.

THE SYNACORE AM-DT SOLUTION

01 **Sub-50 µm Layer-Wise Edge Tracking**
Calibrated in-situ imaging captures produced contours at a 40 µm scale on every layer; micro-scale edge deviations and missing thin-wall segments are computed directly against the MBD slice geometry in the Build-Plate Coordinate System.

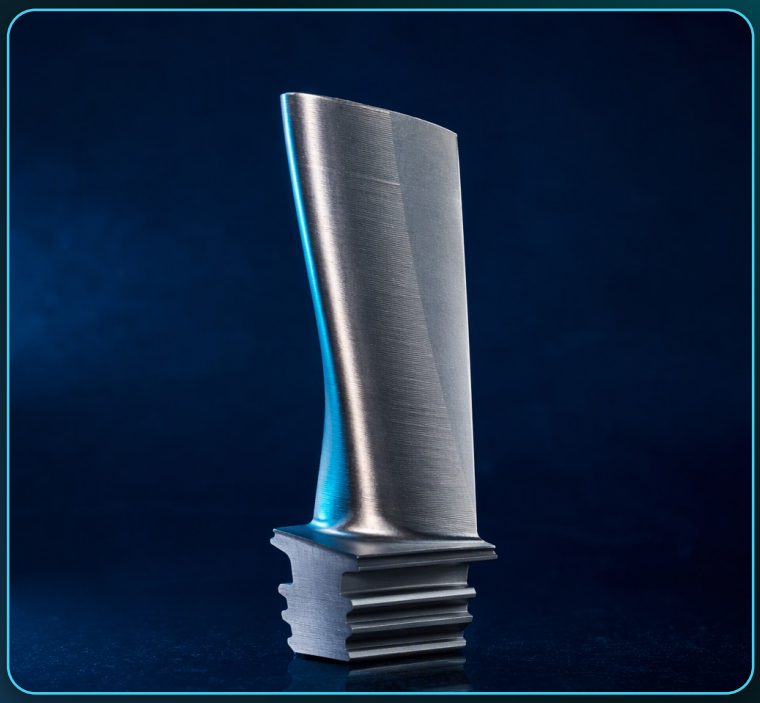
02 **3D Volumetric Deviation Reconstruction**
Layer-wise contour deviations are stacked into an orthorectified 3D digital-twin mesh during the build — a complete volumetric map of internal channel integrity before the part ever leaves the powder bed.

03 **Functional Performance Gating**
Reconstructed internal geometry feeds coupled thermal-fluid surrogates; the twin verifies whether localized fin distortion impacts pressure drop or heat-transfer efficiency against MBD functional thresholds.

SECTION 05 · CASE STUDIES

Pre-qualifying Aero-Engine Load-Bearing Components: Residual Stress & Fatigue Qualification

HIGH-VALUE USE CASE · FRACTURE-CRITICAL STRUCTURES



Metal AM turbine blade in nickel superalloy — subsurface pores and locked-in residual stress act as hidden fatigue crack initiators.

THE CERTIFICATION BOTTLENECK

Turbine blades, structural brackets and rotor components operate under extreme thermo-mechanical cyclic loads. Microscopic subsurface pores, lack-of-fusion flaws and locked-in tensile residual stresses act as hidden fatigue crack initiators. Destructive witness coupons cannot capture local heat accumulation, and costly 100% X-ray CT still cannot measure internal residual stress states.

PRE-QUALIFICATION OUTCOME

Each critical component receives a voxel-resolved Digital Birth Record (DT-DPP) documenting its as-built residual stress state, flaw population and probabilistic fatigue margin — preventing false scrap of high-value alloys, routing CT only to flagged risk zones, and giving regulators physics-backed proof of structural integrity.

THE SYNACORE AM-DT SOLUTION

01 **Subsurface Flaw & Thermal History Localization**
Plume-compensated thermal imaging, layer-wise vision and eddy-current arrays track melt-pool stability and cooling rates across every voxel; remelted anomalies are filtered out and true flaws locked to the Build-Plate Coordinate System.

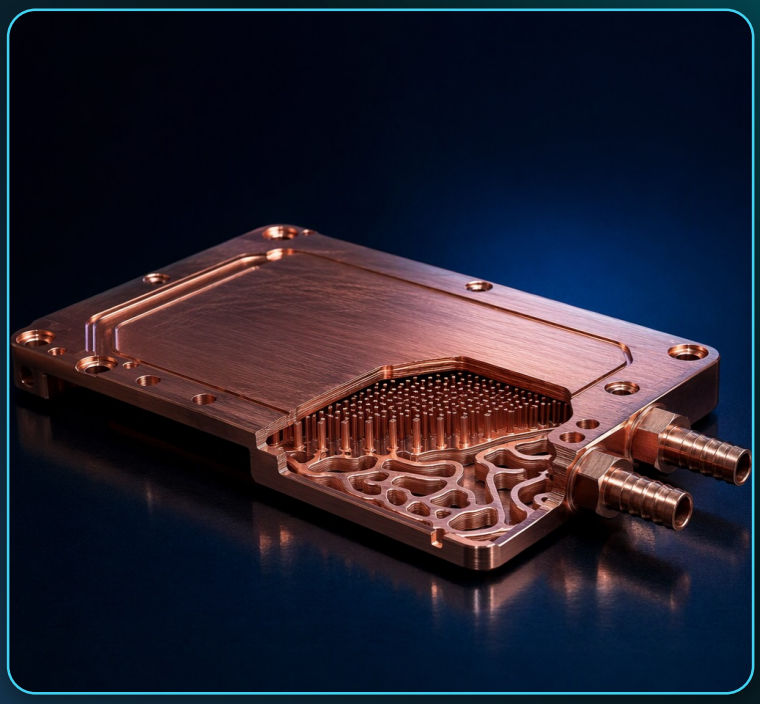
02 **Residual-Stress-Coupled Fracture Equivalence**
Mapped internal defects are converted into Equivalent Initial Flaw Sizes ($\sqrt{area}$) and superimposed onto the solver's 3D residual stress tensor field, evaluating true local stress intensity factors at high-stress fillets and thin-wall transitions.

03 **Probabilistic B_{10} Fatigue Life Gating**
Within a Kitagawa-Takahashi defect-tolerant framework, sensor and model uncertainties are propagated to compute 95% lower-confidence fatigue life (B_{10}); parts pass pre-qualification only when every voxel meets local MBD service-life thresholds.

SECTION 05 · CASE STUDIES

Pre-qualifying Additively Manufactured Liquid Cold Plates: Surface Roughness & Hydraulic Qualification

HIGH-VALUE USE CASE · AI DATA CENTER THERMAL MANAGEMENT



Copper-alloy AM cold plate with pin-fin micro-channels — internal roughness unreachable by stylus profilometers after the build.

THE CERTIFICATION BOTTLENECK

AI data centers rely on single- and two-phase AM cold plates — printed in high-conductivity copper or aluminum alloys — to cool high-wattage GPU and ASIC clusters. Reliability hinges on internal micro-fin roughness (R_a), thin-wall hermeticity and pressure drop (ΔP). Once printed, stylus profilometers cannot reach internal channels, while rough down-skin surfaces risk pumping-power penalties, boiling instabilities and catastrophic coolant leaks.

PRE-QUALIFICATION OUTCOME

Every cold plate receives a serialized Digital Birth Record (DT-DPP) certifying its internal roughness profile, pressure-drop curve, thermal resistance and leak-free integrity — accelerating qualification for custom chip architectures, eliminating destructive-cut sampling, and guaranteeing zero-leak reliability at hyperscale volumes.

THE SYNACORE AM-DT SOLUTION

01 **Physics-Driven Internal Roughness (R_a) Prediction**
Melt-pool hydrodynamics, local overhang angles, powder adhesion physics and calibrated thermal signatures are coupled to predict voxel-by-voxel internal surface roughness across complex micro-channels — no destructive sectioning required.

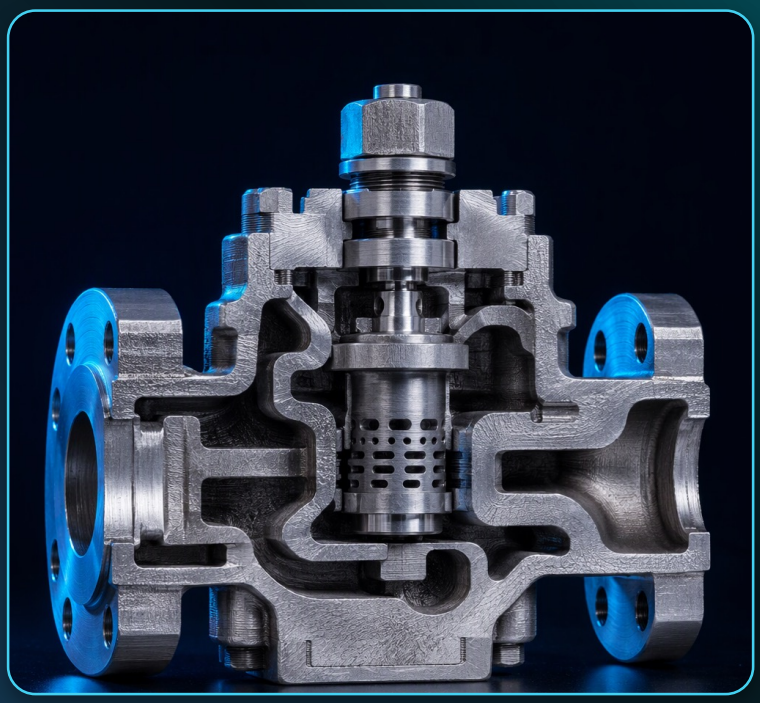
02 **Roughness-Coupled Heat Transfer & ΔP Modeling**
Predicted local R_a maps enter the thermo-fluidic surrogate as spatially varying friction factors and convective multipliers — forecasting true system pressure drop and peak junction temperatures (T_j) before deployment.

03 **Hermetic Wall Integrity & Leak-Free Gating**
Layer-wise edge tracking and subsurface flaw detection verify that ultra-thin channel walls remain free of through-wall lack-of-fusion pores or delamination, gating each plate against MBD pressure-containment and thermal-resistance thresholds.

SECTION 05 · CASE STUDIES

Pre-qualifying High-Integrity Industrial Control Valves: Microstructure & Ductility Qualification

HIGH-VALUE USE CASE · SEVERE-SERVICE FLOW CONTROL



AM severe-service valve body with tortuous multi-stage trim — local ductility loss invisible to external NDE and witness coupons.

THE CERTIFICATION BOTTLENECK

Laser powder bed fusion produces tortuous-path anti-cavitation trims, multi-stage pressure-reducing cages and pressure-retaining bodies in stainless steels and nickel superalloys. Under high-pressure differentials, thermal shocks and water-hammer transients, ductility is the decisive safeguard against sudden brittle fracture — yet localized thermal accumulation and columnar grain growth can silently degrade it, undetectable by external NDE or standalone witness coupons.

PRE-QUALIFICATION OUTCOME

Each valve ships with an auditable Digital Birth Record (DT-DPP) verifying 3D microstructural soundness, local ductility margins and pressure-containment compliance — eliminating destructive burst and tensile-cut testing on custom orders, shortening delivery for critical energy and chemical infrastructure, and ensuring uncompromised operational safety.

THE SYNACORE AM-DT SOLUTION

01 **Thermal-History-Driven Microstructure Prediction**
Tracking layer-wise cooling rates, thermal gradients (G) and solidification velocities (R) across thick-to-thin transitions, coupled phase-field and cellular-automata solvers predict 3D grain morphology, texture and precipitate evolution.

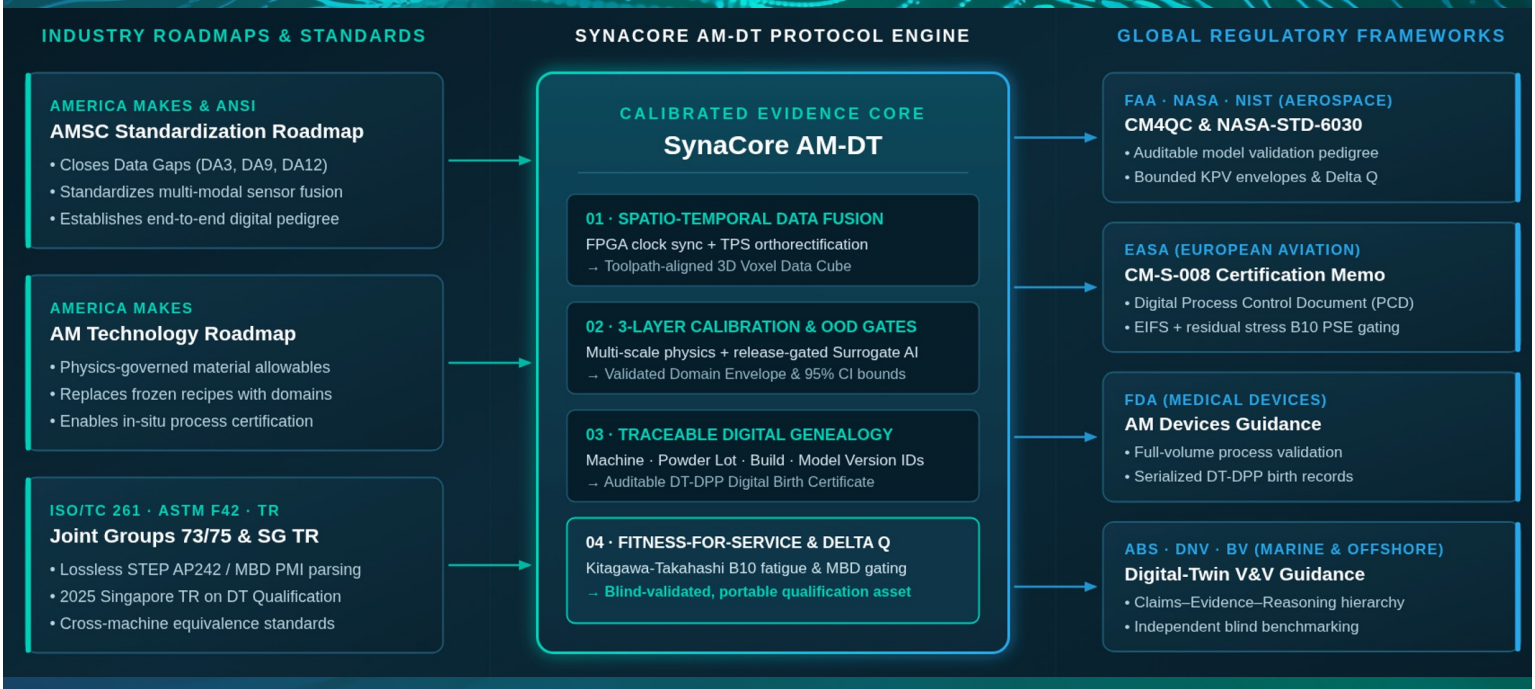
02 **Micromechanical Ductility & Yield-Strength Mapping**
Predicted grain structure, local porosity and heat-treatment response feed crystal-plasticity and ductile-fracture surrogates, mapping spatially resolved elongation-to-failure and yield strength — pinpointing embrittled zones before service.

03 **Pressure-Boundary & Ductility Gating**
Every load-bearing flow passage and pressure-retaining wall is evaluated under peak operating and thermal-shock envelopes, passing only when 95% lower-confidence ductility and toughness exceed MBD and pressure-equipment code minimums.

Regulatory & Standards Alignment

Bridging Technical Protocols to Global Compliance

SECTION 06



SECTION 06 · REGULATORY & STANDARDS ALIGNMENT

Regulatory & Standards Alignment

SynaCore AM-DT's architecture, calibration discipline and data lineage map onto the roadmaps of industry consortia — and onto the airworthiness, spaceflight and medical frameworks administered by regulators worldwide. SynaCore AM-DT is developed with these emerging expectations in view: translating regulatory intent into computable, auditable evidence, while final certification decisions remain, as they should, with the authorities.

7.1 · Aligning with the America Makes & ANSI Standardization Roadmap

The AMSC Roadmap and the America Makes Technology Roadmap identify three gaps that block AM from scaling: no standardized digital formats for in-situ process monitoring, inconsistent multi-modal data registration, and no verifiable data pedigree across the digital thread. SynaCore AM-DT is designed to address all three within its core protocol.

V&V PRINCIPLES EMBEDDED IN SynaCore AM-DT ARCHITECTURE

01 Traceability
Every prediction anchored to its evidence lineage

02 Uncertainty Quantification
Confidence bounds quantified at every voxel

03 Boundary Enforcement
Domain Envelopes with out-of-distribution guardrails

04 Blind Validation
Tested on evidence the model has never seen

Standardized Multi-Modal Data Fusion

Addresses the AMSC data-format gap. FPGA-synchronized off-axis & coaxial sensing, with TPS spatial orthorectification, turns vendor-specific sensor streams into one unified, metric-accurate **3D Voxel Data Cube**.

End-to-End Data Pedigree & Digital Thread

Prediction is able to be anchored to a **Traceable Configuration Fingerprint** — Machine ID · Powder Lot ID · Build ID · Model Version ID — supporting the shift toward physics-governed, portable material and process allowables.

Lossless Model-Based Definition (MBD)

In step with **ISO/ASTM Joint Group 73** on digital product definition: native CAD and STEP AP242 PMI can be parsed directly onto the simulation mesh, preserving design intent from sign-off to post-build verification.

REFERENCE LINKS

America Makes & ANSI AMSC — Standardization Roadmap for Additive Manufacturing v3.0 · ansi.org/standards-coordination/collaboratives-activities/additive-manufacturing-collaborative
ISO/ASTM 52904:2024 · iso.org/standard/82919.html · STEP AP242 (ISO 10303-242) Managed Model-Based 3D Engineering · ap242.org

SECTION 06 · REGULATORY & STANDARDS ALIGNMENT

7.2 · Mapping SynaCore AM-DT to Global Regulatory Frameworks

Regulators are progressively opening pathways for computational modeling to stand alongside physical testing. The Manufacturer-Led Calibration Protocol is designed around the V&V principles these frameworks emphasize.

Regulatory Authority & Framework	Core Regulatory Expectation	SynaCore AM-DT Alignment
FAA · NASA · NIST CM4QC — Computational Methods for Q&C	Auditable validation pedigree, quantified uncertainty bounds, clearly stated applicability limits	**Three-Layer Calibration & OOD Guardrails** — sequential physics calibration, release-gated Surrogate AI, bounded Domain Envelopes
NASA NASA-STD-6030 AM Requirements	Control of Key Process Variables, equipment qualification (IQ/OQ/PQ), powder-reuse tracking, risk-based classification	**Validated Operating Domains & Delta Qualification** — complement KPV control; changes evaluated mathematically, testing scoped to what changed
EASA CM-S-008 Certification Memorandum	Process Control Documents, Statistical Process Control, damage tolerance for primary structures	**Defect-Tolerant Fatigue Gating** — remelting-filtered flaw populations (√area) + residual stress in a Kitagawa–Takahashi framework (B_{10})
FDA AM Medical Devices Guidance	Full-volume process validation across build location, thermal accumulation and powder recycling	**Serialized Digital Birth Records (DT-DPP)** — layer-wise geometric tracking and full-build thermal-history reconstruction
ABS · DNV · BV Digital-Twin V&V Guidance Notes	Structured Claims–Evidence–Reasoning, backed by independent blind benchmarking	**Blind Validation Gate & Singapore TR** — independent blind-build testing, aligned with the 2025 TR and ASTM extension

REFERENCE LINKS

CM4QC — nist.gov/programs-projects/cm4qc · ntrs.nasa.gov/citations/20260001729
NASA-STD-6030 — standards.nasa.gov/standard/NASA/NASA-STD-6030
EASA CM-S-008 (Issue 04) — easa.europa.eu/en/downloads/142437/en
FDA AM Devices Guidance — fda.gov → Technical Considerations for AM Medical Devices
ABS V&V GN 2024 — eagle.org · DNV-RP-A204 — dnv.com

The Actions to Take

Born Pre-Qualified

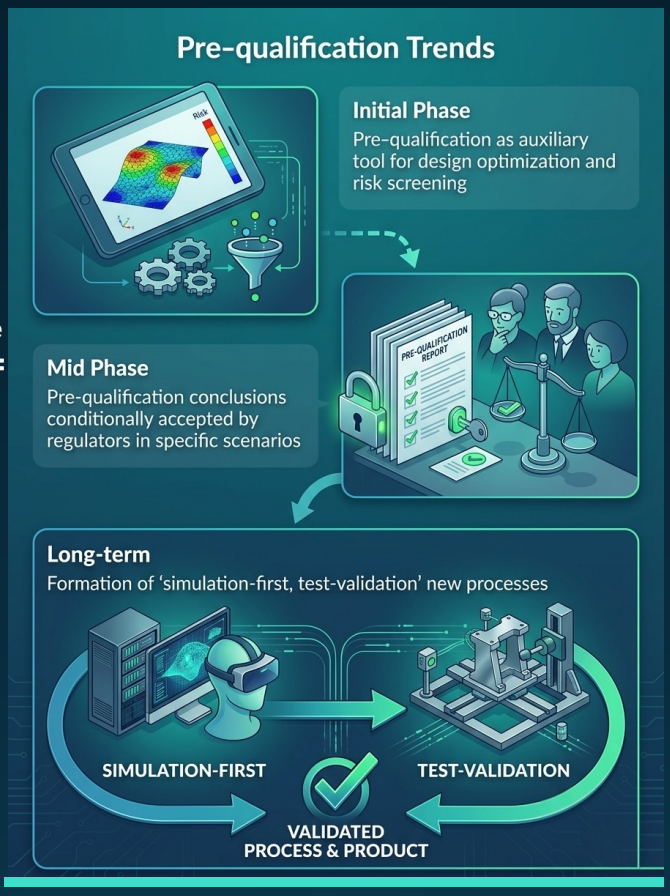
SECTION 07

SECTION 07 · OUTLOOK & CALL TO ACTION

What Each of Us Should Do Now

We expect pre-qualification to arrive in three waves. **Now — auxiliary:** digital twin prediction guides design optimization and risk screening, concentrating physical specimens where information is densest. **Within two to three years — parallel:** calibrated predictions are conditionally accepted by certification bodies in defined scenarios, running alongside reduced test campaigns, as the Technical Reference matures into **shared confidence ranges.**

Beyond that—integrated: simulation-first, test-confirmation becomes the default qualification route, and the digital birth certificate becomes a verifiable, portable credential of process integrity. A certificate verifiable anywhere frees manufacturing from geography—empowering regulators to focus on high-level oversight rather than repetitive physical verification—and qualification ceases to be a cost center, becoming a design asset whose evidence is reusable across part families, materials and sites.



Evolution Timeline Expected & Key Milestones

Coming Now	2-3 Years	3+ Years
Auxiliary Pre-Qualification	Parallel Qualification	Integrated Qualification

Machine OEMs

Expose synchronized machine and process data interfaces; support configuration fingerprints natively; co-develop machine-family equivalence so your customers' knowledge survives hardware generations.

Part manufacturers

Start with one part family: run baseline, DOE(design of experiments) and boundary builds; archive evidence as versioned assets; adopt delta qualification for your next change instead of another full requalification.

Powder & material suppliers

Ship every lot with a digital material passport — chemistry, morphology, flow and reuse metadata — so powder truth can travel with the powder and feed calibration directly.

Classification societies & regulators

Define the confidence ranges the proposed standards work item calls for; pilot technical-report-based pre-qualification on real components; accept calibrated model lineage as evidence alongside test reports.

Standards community & research institutions

Join the pre-qualification journey and bring your most challenging parts: contribute blind benchmark builds across machines and materials, and align how models are verified and their uncertainty measured. Standards are shared infrastructure: the sooner we build them together, the sooner certification stops being the bottleneck and starts being the industry's most credible promise.

SYNACORE Vision

Evolving Manufacturing

SYNACORE Mission

Drive Physical Manufacturing with Virtual Intelligence

Request trial access at www.synacore.net. This is a partnership: your operational evidence directly sharpens the platform, while you develop proprietary calibration assets unique to your processes. If you encounter an issue or have a suggestion, we would love to hear from you.

Let's advance manufacturing together — drive physical manufacturing with virtual intelligence.

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