Automated Simulation Workflow for 3D-Printed Scintillator Phantoms in Radiotherapy Planning

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Abstract

G4RT is a simulator based on Geant4, with a built-in capability to convert CAD assemblies into a tabular geometry database and create complete detector/phantom geometry based on this DB. A single external TOML-based file governs geometry options, material mapping, physics lists with per-region cuts, scoring, and I/O. Deterministic multi-threaded runs are ensured by recording all provenance (TOML snapshot, library versions RNG seeds). Beams can be defined as Generic Particle Sources or imported from IAEA phase-space with simple energy/angle/field filters for clinical realism. The NTuple output (ROOT) captures cell/voxel identifiers, positions, energy deposit and dose, process/track tags, and optional parent–child relations. Together, this CAD → DB → Geant4 pipeline shortens iteration cycles, improves auditability, and enables reproducible comparisons against measurements when validating 3D-printed scintillator phantoms.

Key Contributions

- **DB-driven geometry**: entire CAD assembly encoded as rows; programmatic build, no hard-coded volumes.
- **Config as the single source of truth**: one external TOML fully defines geometry (selection & transforms, materials), physics (list & per-region cuts), source/PHSP, scoring, run control (events/threads/seed), and I/O; LogSvc stores a snapshot for deterministic re-runs.
- **Deterministic MT runs**: per-thread analysis buffers, sparse I/O flushes, reproducible RNG seeds in logs.
- **PHSP realism**: IAEA phase-space ingestion with simple energy/angle/field filters for clinically plausible beams.

Evolution of the CAD → Sim Workflow

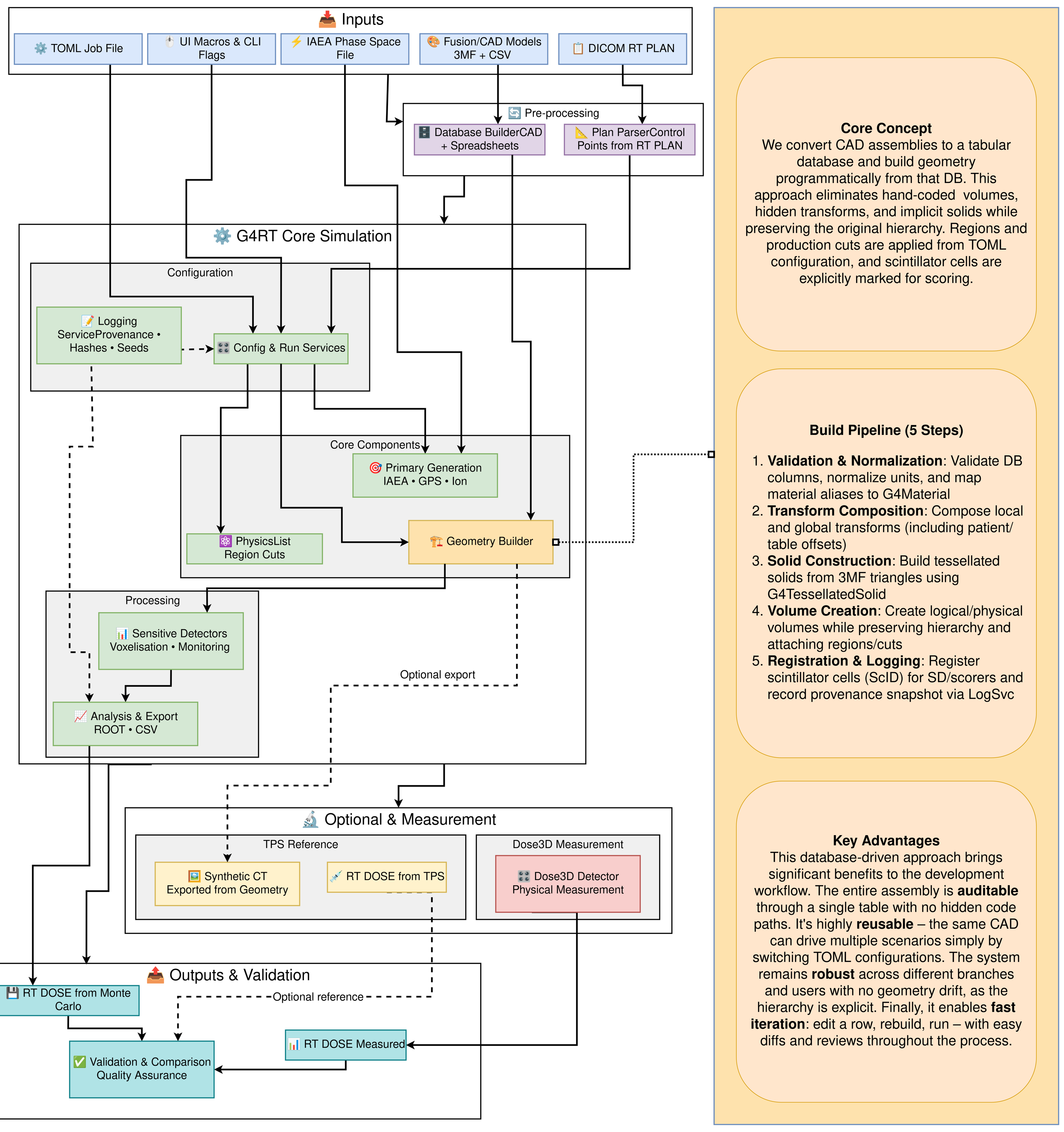
Phase I (FreeCAD era). Assembly exported as a **series of STLs**; Python script assigned materials and positioned parts. *Pros:* quick prototyping. *Cons:* manual steps, fragile naming, limited auditability.

Phase II (Fusion + DB). Fusion 360 exporter ⇒ **3MF + CSV**; DB builder consolidates into 3MF based Excel/CSV DB with run metadata & hashing; **DBGeoBuilder** ingests directly in G4RT. *Pros:* automation, reproducibility, speed, single source of truth.

PHSP (IAEA) Beam Realism

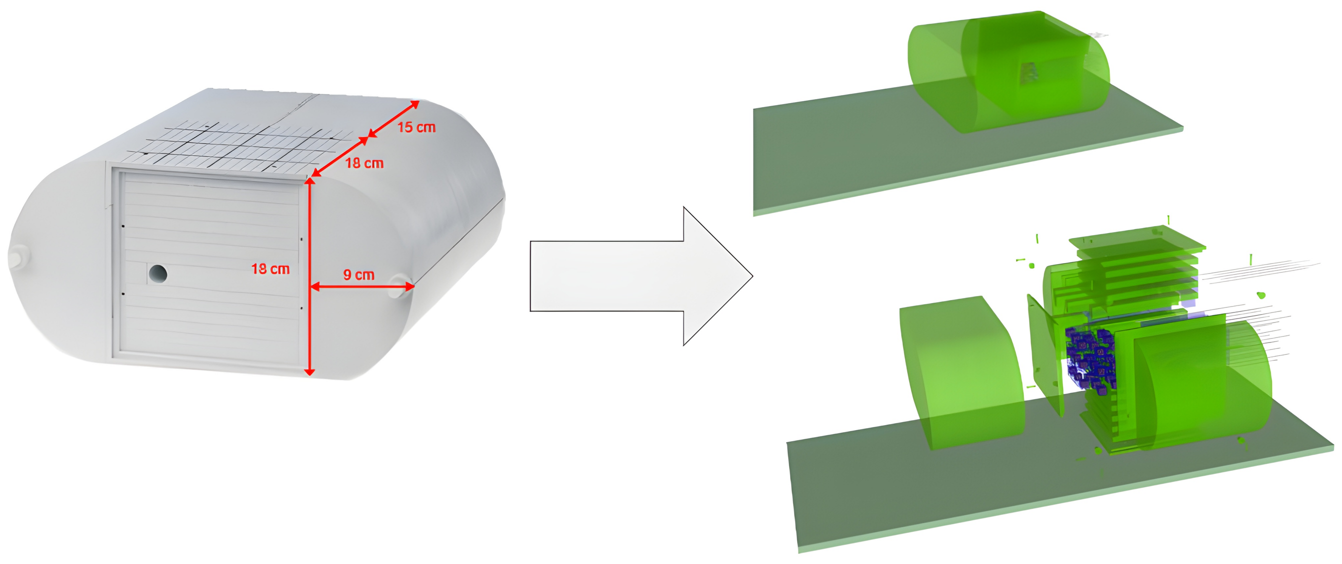
- IAEA PHSP ingestion with lightweight energy/angle/field filters; unit normalization.
- Deterministic per-thread/run seeding; MT-ready implementation.
- Clinically plausible beams for phantom testing and dose calibration.

CAD → DB → Geometry (Core Idea)



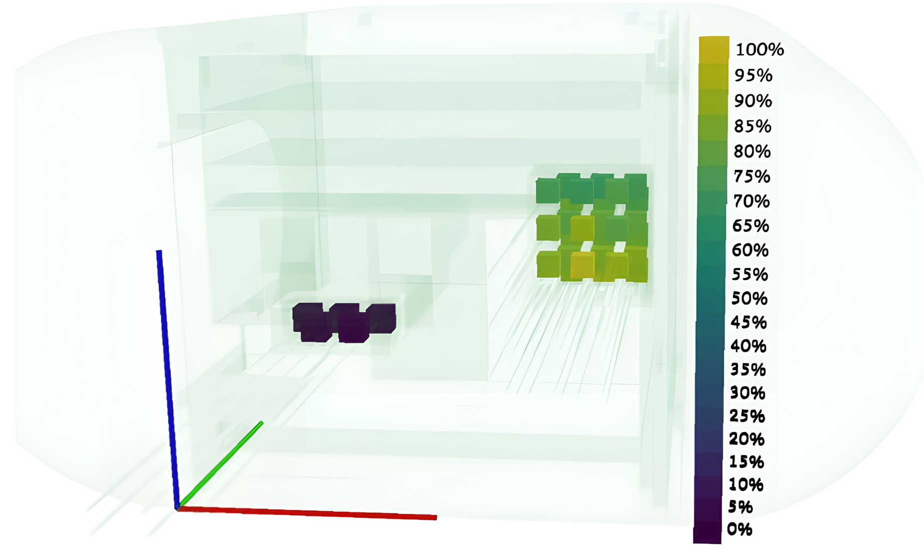
From Object to Geant4 (visual)

Side-by-side view of the physical object and the imported to Geant4 geometry.



Results & Validation (example)

- **Dose map (Gy)**: 2D slice or 3D projection over the phantom; annotate build-up and high-gradient regions.
- **PDD and Ad-depth profiles**: compare simulation vs measurement (if available); report basic metrics ($\gamma index$ / dose difference).
- **Reproducibility**: figure generated from a run with recorded TOML, hashes, and RNG seeds (LogSvc).



Why It Matters

We replace fragile, hand-coded geometry with a transparent and reproducible CAD → DB → G4RT pipeline. Clinical realism (table, passive elements, PHSP), precise 3D-printed scintillator modelling, and full provenance (TOML + hashes + RNG seeds) shorten iteration cycles and enable safer, auditable comparisons against measurements in radiotherapy workflows.

Conclusions

- **DB-driven geometry:** the CAD → DB → Geant4 pipeline replaces hand-coded geometry with a transparent and auditable workflow. Every component of the CAD assembly is preserved in tabular form, ensuring that changes in design can be propagated directly to the simulation.
- **Reproducibility by design:** all simulation runs are accompanied by full provenance, including TOML snapshots, input file hashes, library versions, and per-thread RNG seeds. This guarantees that results can be repeated and independently reviewed.
- **Clinically plausible beams:** by importing IAEA phase-space files with energy, angle, and field filters, the system reproduces realistic treatment conditions.
- **Portable analysis:** outputs are written in well-documented formats (ROOT/CSV) with embedded units and schema versioning, enabling straightforward use in Python and ROOT workflows. This facilitates consistent analysis across teams and simplifies validation against experimental measurements.
- **Future directions:** we plan to extend the workflow with richer transform handling, automated QA checks, selective I/O, and visual regression tools. These improvements will enhance robustness and reduce the turnaround time for geometry updates, making G4RT a reliable platform for iterative design and validation of radiotherapy phantoms.

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