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G4RT — Geant4-Based Simulation Platform for Radiotherapy Phantom Studies

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We introduce G4RT, a reproducible simulation framework that transforms complete computer-aided design assemblies into Geant4-compatible detector geometries via a fully auditable computer-aided design-to-database (CAD → DB) workflow. Exports from the Fusion 360 CAD platform (3MF and CSV) are normalized into a schema-constrained database and processed by a database-driven geometry builder, which preserves hierarchical structure, material definitions, and spatial transformations while generating tessellated solids and registering sensitive detector volumes. Physics settings, cut-offs, sources (analytic or International Atomic Energy Agency phase-space files), and scoring parameters are centrally configured using TOML, a human-readable configuration file format. We assess geometry fidelity, dosimetric accuracy via gamma analysis, and computational performance under multithreading, demonstrating reduced iteration times and enhanced auditability compared to hand-coded geometries. This approach is particularly suited for experiments employing 3D-printed scintillator phantoms under clinically realistic beam conditions.

topics: Geant4, radiotherapy, 3D-printed scintillator phantoms, database-driven geometry

1. Introduction

Geant4 [1] is a widely used toolkit for particle transport simulations. When constructing phantoms or detectors, it is essential to maintain accurate and verifiable geometry descriptions to ensure reproducibility of simulation results. While hand-coded `G4VSolid` and `G4LogicalVolume` structures provide flexibility, they are prone to errors and become increasingly difficult to modify in large-scale geometries. To address this, we have developed a streamlined workflow in the G4RT toolkit that translates computer-aided design (CAD) assemblies into Geant4 geometries via a database-driven process. First, CAD assemblies are exported to open formats, specifically 3MF files with CSV metadata for each component. These exports are then consolidated into a version-controlled geometry database using our `DatabaseBuilder` tool. The proposed pipeline integrates with our configurable runtime system (G4RT) and is designed with three primary objectives: maintaining consistent units, ensuring full traceability to the original sources, and achieving clinically realistic conditions through phase-space (PHSP)-based radiation sources [2, 3].

The builder performs several critical tasks in the simulation workflow. It combines local and global transformations, generates `G4TessellatedSolid` objects from 3MF triangle meshes, constructs logical volumes, and places physical volumes within the geometry while preserving the original hierarchical structure. Regions, which define spatial domains within the geometry for applying specific simulation parameters such as production cuts, are specified alongside these cuts in a single `config.toml` file [4]. The file also configures physics lists (electromagnetic, hadronic, and optical processes), radiation sources, scoring definitions and NTuples, run control parameters, and output specifications. When a `ScID` is provided (which serves as an identifier for read-out channels), sensitive detectors and associated scorers are automatically registered. Reliable multithreading is achieved by recording random seeds, employing thread-local analysis buffers, and performing sparse input/output (I/O) flushing.

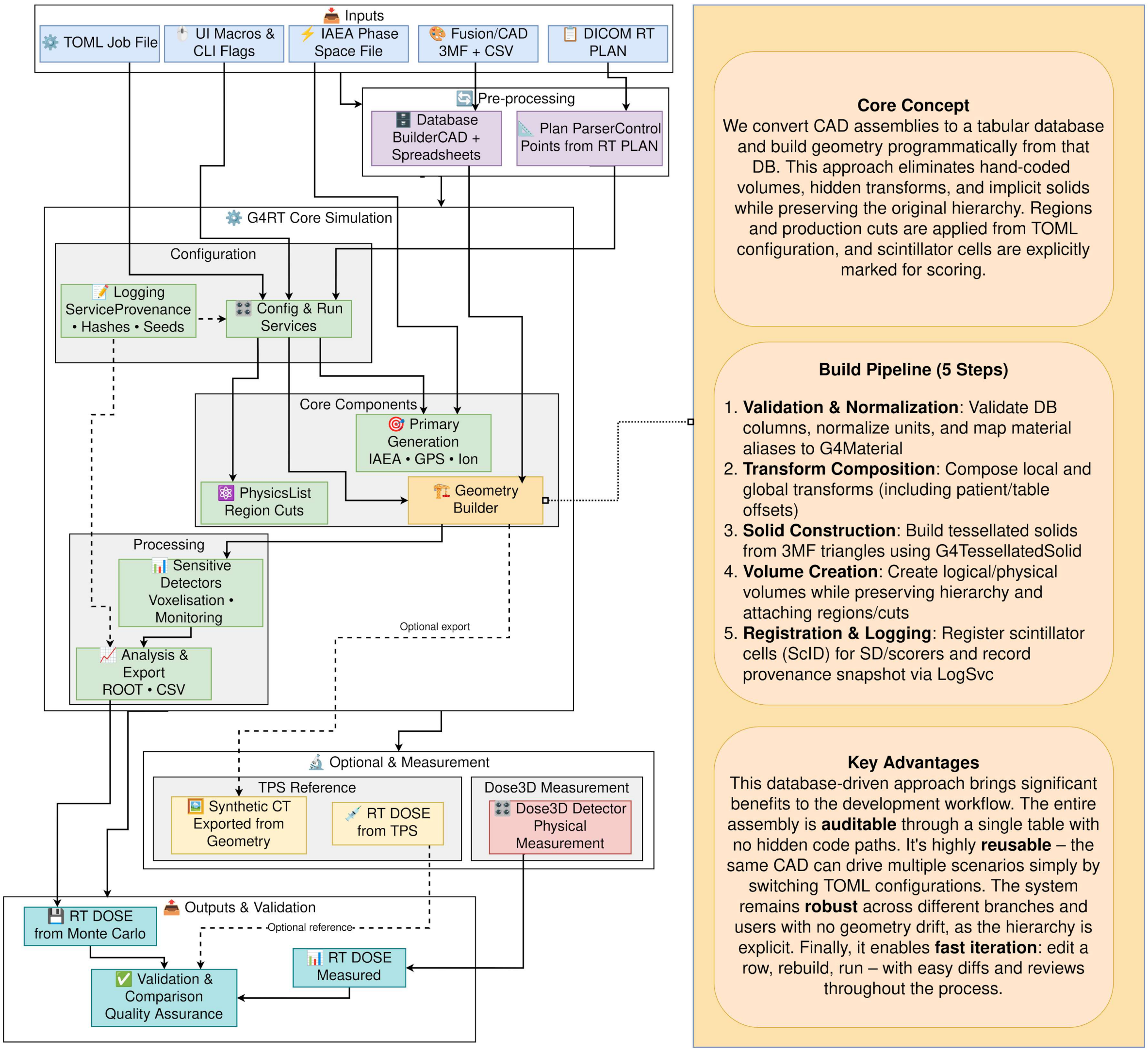

Fig. 1. G4RT simulation workflow architecture. Overview of the data flow from input files through core simulation components to output validation, showing the integration of CAD models, treatment planning data, and Monte Carlo dose calculation.

Typically, incorporating CAD models into Geant4 involves either importing tessellated meshes, as implemented in CADMesh [5, 6], or using XML-based geometry interchange via GDML [7]. Prior research has developed PHSP-based sources to represent clinical beam conditions, based on the International Atomic Energy Agency (IAEA) database [2, 3]. Dose comparisons are commonly performed using the γ-index introduced by Low et al. [8] and its subsequent refinements [9], widely applied in radiotherapy quality assurance. To support accurate and reproducible dosimetric evaluation, our approach treats the CAD export and database as a locked-down *system of record*, with explicit unit definitions and a complete history tracing all steps from export through database, geometry builder, and analysis. This is achieved while retaining the flexibility of tessellated solids and a database-driven workflow.

2. G4RT workflow for translating CAD models into Geant4 geometries

The overall architecture of the G4RT workflow, illustrating how CAD models are converted into Geant4 geometries and integrated with treatment planning and dose calculation, is shown in Fig. 1. The following sections describe each component of the workflow, highlighting specific aspects of geometry handling and physics configuration.

2.1. Database schema for CAD exports

Fusion 360 exports comprise the triangular mesh and assembly hierarchy (3MF format), accompanied by a CSV or XLSX table specifying material assignments and geometric transformations. The database schema enforces mandatory columns and explicit units. During import, all units are standardized to millimetres and degrees, and parent–child relationships are verified for consistency. Material aliases are mapped to `G4Material` definitions, either from National Institute of Standards and Technology (NIST) standards or user-defined materials, with optional overrides for density and production cuts. Table I summarizes the minimal CAD-to-database schema employed by `DBGeoBuilder`, with units enforced at load time.

TABLE I

Minimal CAD-to-database schema used by DBGeoBuilder (units enforced at load time)

Field	Unit/type	Example
VolumeName	string	Scin_Cell_042
Material	alias	PLA_Scint_A
T_x, T_y, T_z	mm	12.5,0.0,35.0
R_x, R_y, R_z	deg	0,0,90
ScID	string	Cell_ID_042

2.2. DBGeoBuilder — database-driven geometry, physics, and scoring management

The builder performs several key functions: it combines local and global transformations, generates `G4TessellatedSolid` objects from 3MF triangle meshes, constructs logical volumes, and places physical volumes while preserving the original hierarchical order. Simulation regions and production cuts are applied according to a single `config.toml` configuration file (`*.toml` is a human-readable format for specifying parameters in a structured and machine-parsable way) [4].

The configuration file also defines physics lists (electromagnetic, hadronic, and optical processes), radiation sources, scoring primitives, and NTuples (structured data tables stored in ROOT format for per-event simulation outputs), run control parameters, and output specifications. When a `ScID` is provided, sensitive detectors and associated scorers are automatically registered.

Several complementary strategies ensure reproducible parallel execution: each thread records its own random number seeds to guarantee deterministic results, analysis data are stored in thread-local buffers to prevent race conditions, and input/output operations are performed in a staggered manner to minimize contention and ensure orderly results writing.

2.3. Phase-space approach to radiation source modeling

Primary particle generation supports both analytic sources and IAEA phase-space (PHSP) file ingestion with configurable energy, angle, and field filters. Consistent per-thread and per-run seeding ensures complete reproducibility [2, 3].

3. Experiments and results

The proposed workflow was evaluated using multiple representative configurations, ranging from a simple calibration phantom to a modular scintillator array and a clinically realistic setup including a treatment table and applicators. All simulations employed identical TOML-based specifications for physics lists, production cuts, and beam geometry.

3.1. Metrics and evaluation

The workflow was analyzed with respect to core metrics, such as:

- Dosimetric accuracy. γ-index pass rates were computed at 3%/3 mm and 2%/2 mm criteria [8, 9].
- Performance. Import and build time, memory footprint, event throughput (events/s), and multithreading efficiency were evaluated.
- Ablation studies. Individual features such as region-specific cuts, step filters, and sparse I/O were selectively disabled to quantify their impact.
- Baseline comparison. All results were compared against hand-coded geometries produced by conventional Geant4 workflows.

3.2. Dosimetric results

The workflow achieved γ-index pass rates at 3%/3 mm, exceeding typical clinical acceptance thresholds, with the stricter 2%/2 mm criterion highlighting sensitivity to voxel resolution and production cut settings. Phase-space (PHSP)-based sources provided improved agreement in penumbra regions relative to analytic beams.

4. Conclusions

Utilizing a database-driven approach facilitates geometry modifications while maintaining full auditability. This methodology reduces coding errors and accelerates updates, as changes in CAD models do not necessitate manual adjustments in the simulation code.

Phase-space (PHSP)-based sources facilitate the integration of clinically relevant beam data into simulations. However, this approach presents several challenges. The system is sensitive to defective meshes, particularly those with missing faces or non-standard geometries, and the automatic management of complex configurations remains an area for improvement.

Unit handling is generally reliable, although certain atypical cases still require verification. Additionally, errors present in the original PHSP files propagate into the simulations. Future development will focus on several areas: expanding transformation capabilities beyond standard operations, implementing automatic quality assurance through geometric comparisons and visual inspections, enhancing physics configuration management for distinct regions, and establishing continuous integration with comprehensive regression testing.

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References

[1] J. Allison, K. Amako, J. Apostolakis et al., *Nucl. Instrum. Methods Phys. Res. A* **835**, 186 (2016).

[2] International Atomic Energy Agency, Phase-space Database for External Beam Radiotherapy, 2024.

[3] R. Capote, R. Jeraj, C.M. Ma, D.W.O. Rogers, F. Sanchez-Doblado, J. Sempau, J. Seuntjens, J.V. Siebers, in: *Consultants' Meeting on Phase-space Database for External Beam Radiotherapy*, INDC(NDS)-0484, 2006.

[4] T. Preston-Werner, P. Gedam, D. Ostroske et al., TOML v1.0.0. 2021.

[5] C.M. Poole, I. Cornelius, J.V. Trapp, C.M. Langton, *Australas. Phys. Eng. Sci. Med.* **35**, 329 (2012).

[6] C.M. Poole, I. Cornelius, J.V. Trapp, C.M. Langton, *IEEE Trans. Nucl. Sci.* **59**, 1695 (2012).

[7] R. Chytracek, J. Mccormick, W. Pokorski, G. Santin, *IEEE Trans. Nucl. Sci.* **53**, 2892 (2006).

[8] D.A. Low, W.B. Harms, S. Mutic, J.A. Purdy, *Med. Phys.* **25**, 656 (1998).

[9] D.A. Low, J.F. Dempsey, *Med. Phys.* **30**, 2455 (2003).