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A CRITICAL ANALYSIS OF THE DIRECTION OF BIM DEVELOPMENT: FROM CAD THROUGH FILE-BASED APPROACHES AND SAAS TO GRANULAR DATA

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SUMMARY*: Data exchange in the AECOO industry remains constrained by the closed architectures of BIM tools and the hidden dependency of open standards such as IFC on incompatible geometric kernels. This paper asks whether kernel-independent, mesh-based formats specifically glTF and USD can address the interoperability, scalability and data-access limitations inherent in current kernel-dependent BIM paradigms. A qualitative, review-critical analysis was conducted, combining a comparative assessment of data standards (IFC, glTF, USD), technical documentation of geometric kernels and platforms, and case-based evidence from commercial and R&D projects. The analysis shows that mesh-based formats, combined with structured non-geometric data stored in formats such as JSON, CSV or SQL, offer a plausible and increasingly practical alternative to kernel-dependent workflows for a significant range of AECOO use cases, particularly those involving visualisation, simulation, robotics and AI. These findings are relevant to BIM researchers, software developers, and AECOO practitioners seeking to reduce vendor dependency and build scalable, AI-compatible data environments. Future research should empirically validate the performance of granular, mesh-based data systems across diverse project scales and disciplines, and investigate standardised methods for converting parametric data to mesh representations without critical loss of fidelity.*

KEYWORDS*: BIM (Building Information Modeling), new approach, critical analysis, openBIM, granular data, IFC (Industry Foundation Classes).*

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1. INTRODUCTION

In the Architecture, Engineering, Construction, Owners and Operators (AECOO) domain, digital design and coordination processes are increasingly mediated by advanced BIM (Building Information Modelling) tools such as Autodesk Revit or Graphisoft Archicad (Wu et al. 2021) , but their closed structure prevents the free combination of data (Waas, 2022), which is standard in other industries such as mechanical (Gao et al. 2003). The goal of BIM is not to have models but to inform those who have some work to do (Turk, 2025). In both the design and subsequent implementation of a project, calculations, primarily of cost and time, are crucial (Mörtl & Schmied, 2015; Szóstak 2021). The foundation, however, remains the data itself, because while there are many ways, to model and visualize it, the most relevant are still time and cost calculations (Plebankiewicz, Zima, & Wieczorek, 2021), which become useful information over time. Based on specific rationale, the client/principal collects requirements and parameters (Zima & Mitera-Kiełbasa, 2021), which are then entered into CAD (Computer Aided Design) or BIM applications, where often very sophisticated and complex geometry is created (Borkowski & Kubrat, 2024) to then generate new parameters, mainly volume and number of elements, necessary to produce a bill of materials (Alathamneh, Collins, & Azhar, 2024). As a rule, geometry is not needed for the calculations themselves. Usually, volume and quantity measurements for groups of elements will suffice. The problem is that in the current state of knowledge and technology, volume parameters cannot be automatically calculated without geometry. CAD/BIM programs use so-called geometric kernels for this - millions of lines of code that convert parametric geometry defined by points into specific volume values, which can only then be used in calculations (Konopatskiy & Bezsolnov, 2025). It is now possible to automate design using visual and parametric programming tools such as Dynamo (Kochański & Borkowski, 2024) or Grasshopper (Koszewski, Franczuk & Argasinski, 2021). Solutions of this type can generate entire CAD/BIM designs based on only 10-20 parameters. The public purchaser/private client generally collects the project information and saves it in an EIR, e.g. in an Excel sheet (Zima & Mitera-Kiełbasa, 2019). From there, the data can be automatically transferred to CAD/BIM. When parameters are translated into the CAD/BIM structure, the program adds new, further geometry and volume information. Thus, access to the original data is lost, and the entire concept - from initial assumptions to client requirements - becomes trapped in a closed, native format.

Research to date in the BIM area focuses primarily on interoperability at the level of the logical IFC data structure (Li & Xu, 2024) or application implementations (Sampaio, Gomes & Farinha, 2021), ignoring the issues of strong dependence on external geometric kernels and incompatibility of geometric parameters between different systems. The literature lacks comprehensive analyses of the impact of computational kernel architecture on the ability to integrate data and its subsequent use in platform-independent environments. At the same time, there is a dynamic development of open formats based on mesh geometry, e.g. glTF (GL Transmission Format), USD (Universal Scene Description), which can enable the establishment of a new paradigm for design data management.

Based on current knowledge and technology, the following has been defined:

Research problem: Current methods of data exchange in BIM, based on parametric formats requiring geometric calculation kernels, generate limitations in interoperability, scalability and data access.

Hypothesis: Triangular mesh-based formats (e.g., glTF, USD) have the potential to serve as alternatives or complements to traditional BIM formats, but their usefulness depends on an analysis of the benefits and limitations in various AECOO applications.

The subject of this paper is to analyze this change and identify technological and systemic barriers to moving away from a file-oriented paradigm and geometric kernels.

Existing research on BIM interoperability has predominantly focused on the logical and semantic layers of data exchange. A substantial body of literature addresses the IFC data model, its EXPRESS-based schema, and the challenges of mapping proprietary BIM structures to the IFC standard (Li & Xu, 2024; Laakso & Kiviniemi, 2012; Jiang et al., 2019). Other studies examine application-level interoperability, comparing how different BIM authoring tools import and export IFC files and identifying discrepancies in geometric and semantic translation (Sampaio, Gomes & Farinha, 2021). The CDE paradigm and its role in coordinating file-based workflows have also received considerable attention (Dolla, Venkatachalam & Kumar Delhi, 2024; Borkowski et al., 2023).

However, this literature largely treats the geometric computation layer as a transparent infrastructure element. The dependency of every IFC implementation on an external geometric kernel — such as OpenCascade, Parasolid or Shape Manager — and the fundamental incompatibility between kernels developed by different teams using different mathematical approaches (Ingram, 2020) are rarely foregrounded as a systemic barrier to interoperability. Studies that do acknowledge kernel complexity typically do so in the context of mechanical CAD (Pratt, Anderson & Ranger, 2005; Gao et al., 2003) rather than in the specific context of AECOO workflows, where geometric requirements are often far simpler than those assumed by the kernels in use.

What the literature does not address is the following chain of reasoning: (1) that the geometric kernels underlying IFC are architecturally incompatible with one another, making true format-level interoperability structurally unattainable regardless of schema-level standardisation; (2) that this kernel dependency is disproportionate to the actual geometric complexity required by most AECOO use cases; and (3) that this mismatch creates a systemic opportunity for alternative, kernel-independent data paradigms — specifically mesh-based formats such as glTF and USD — to serve as practical complements or substitutes in selected workflows.

The novel contribution of this paper is threefold: (1) it identifies the architectural incompatibility of geometric kernels as a root cause of BIM interoperability limitations, a factor that is largely absent from the existing literature, which focuses on schema-level standardisation; (2) it demonstrates that this kernel dependency is disproportionate to the geometric complexity actually required by most AECOO workflows, creating a systemic mismatch; and (3) it proposes and comparatively assesses a mesh-based, kernel-independent data paradigm (using glTF and USD) as a plausible complement to traditional BIM approaches for selected use cases.

2. MATERIALS AND METHODS

The purpose of this paper was to critically analyze current methods and paradigms in BIM, with a focus on the role of geometric kernels, data exchange formats, and granular approaches to design data. A qualitative approach based on the technology case study method and critical systems analysis was used.

The analysis used:

- the author's practical experience of implementing BIM systems and parametric tools (Dynamo, Grasshopper) in architectural and engineering projects,
- comparative analysis of data standards (IFC, glTF, USD, COLLADA, OpenGL) taking into account their data architecture and technical requirements (including dependencies on geometric kernels, e.g. OpenCascade),
- analysis of technical documentation and specifications of geometric data standards and environments such as Autodesk Revit, ArchiCAD, Unreal Engine, Omniverse,
- review of academic and industry literature on data integration in design environments (CAD/BIM), automation of data flows, and open spatial data formats.

Methodologically conducted:

- Analysis of the IFC data model in terms of its dependence on closed geometric structures and the limitations of various kernel implementations.
- Comparison of the efficiency and availability of data in tools based on parametric formats (Revit, IFC) vs. grid-based formats (glTF, USD).
- Evaluate the potential to transform data from proprietary files to structured data (CSV, JSON, SQL) for further analytical processing.
- Assessing the potential for automating design and costing processes using structured data and AI (Artificial Intelligence).

The analysis followed a structured four-step analytical framework designed to ensure transparency and reproducibility:

- Step 1 – Identification of data representation paradigms. Three principal paradigms were identified from the literature and industry practice: (a) kernel-based parametric representations (IFC, native BIM formats), (b) mesh-based open representations (glTF, USD), and (c) structured non-geometric data formats (JSON, CSV, SQL). These categories served as the comparative axes for the remainder of the analysis.

- Step 2 – Characterisation of each paradigm. For each paradigm, the following dimensions were systematically examined: (i) dependency on geometric kernels, (ii) openness and portability of the format, (iii) ability to separate geometry from non-geometric attributes, (iv) compatibility with AI, real-time simulation and robotic workflows, and (v) scalability across project types and sizes. Evidence was drawn from technical specifications, documented workflows and the author's project experience.
- Step 3 – Comparative assessment. The three paradigms were compared along the dimensions defined in Step 2. The comparison was qualitative, based on documented capabilities and observed behaviour in real projects, and is summarised in the Results section (including Figures 2 and 3, which reflect the author's expert judgement on a qualitative ordinal scale (Low / Low–Moderate / Moderate / Moderate–High / High).).
- Step 4 – Synthesis and formulation of design-system recommendations. The findings from Steps 1–3 were synthesised to identify systemic barriers, trade-offs and plausible development trajectories for BIM data management, leading to the conclusions and future research directions presented in the final sections of this paper.

The analysis draws on four main categories of sources:

Standards and technical specifications

- IFC schema and documentation (STEP/EXPRESS-based meta-data and geometric part).
- Documentation of open mesh formats (glTF 2.0, USD) and related ecosystems.
- Documentation of geometric kernels and platforms (e.g. OpenCascade, proprietary kernels such as Shape Manager and Parasolid) as referenced in vendor and research materials.

Software platforms and environments

- BIM authoring tools relying on parametric kernels (e.g. Autodesk Revit, Graphisoft Archicad and comparable platforms).
- OpenBIM/open-source initiatives (e.g. BlenderBIM/Bonsai) working with IFC and mesh formats.
- Game-engine and real-time environments using triangular meshes (e.g. Unreal Engine, NVIDIA Omniverse, Blender).

Documented workflows and case-based evidence

- Selected project workflows using CDE/SaaS platforms with file-based collaboration (e.g. IFC + native BIM formats).
- Selected project workflows using mesh-based pipelines (e.g. glTF/USD with game engines or digital twins). These workflows are drawn from commercial and R&D projects in which the author participated, with project-specific details anonymised.

Academic and industry literature

- Peer-reviewed publications on IFC, openBIM, geometric kernels, data integration, CDEs and AI-based automation in design and construction.
- Industry reports and white papers on digital twins, robotics and real-time simulation in the AECOO domain.

All analysis was conducted based on available research data repositories, standards documentation and own implementation experience from commercial and R&D projects. The paper is of a review-critical nature, aimed at formulating design-system conclusions rather than empirical validation under laboratory conditions.

The author’s practical involvement in BIM implementations, parametric design (Dynamo, Grasshopper) and integration with real-time environments is used as a structured source of case-based evidence rather than anecdotal opinion. The cases inform the identification of typical bottlenecks (e.g. kernel-related interoperability issues, over-modelling, file-based CDE limitations) and help illustrate how alternative, granular data strategies can be implemented in practice.

The paper does not include controlled experiments, large-scale surveys or quantitative performance benchmarks. The evaluation is qualitative and comparative, focusing on architectural and systemic characteristics of different data paradigms rather than on numerical performance metrics. As such, the conclusions should be seen as hypotheses and design–system recommendations that require further empirical testing on real projects and across different AECOO subdomains.

3. RESULTS AND DISCUSSION

3.1 CAD/BIM

CAD/BIM tools were originally designed as monolithic desktop applications focused on geometry modeling and technical drawing production, with less focus on data analysis (Borkowski, 2023). Despite the evolution toward collaborative environments like CDE (Common Data Environment) or SaaS (Software as a Service), most are still based on native, closed file formats that are difficult to analyze or process without dedicated software (Brelih & Klinc, 2024). The basic problem is that the data in BIM models is inextricably linked to the geometry and graphical representation (Gan, 2022). The structure of the models in tools such as Autodesk Revit or Graphisoft Archicad combines design, graphical and geometric logic into a single set, making it difficult to extract information for cost, time, scheduling or simulation analyses.

Unlike modern approaches based on granular data (Mayer & Bechthold, 2020), where geometry and attributes are separated, CAD/BIM systems require parsing geometric kernels, format conversions, exports and version dependencies. This not only adds complexity, but also makes integration with AI, game engines or simulation environments difficult. As a result, while BIM nominally serves to manage building information, in practice it acts more like a graphical system than an information system. This raises the need to rethink the place of CAD/BIM tools in the AECOO ecosystem, not as an operational center, but as a component of one of many data sources.

Currently, there are open source applications like Bonsai (Blender BIM) and other products on the market in the openBIM idea, which is still developing (Jiang et al., 2019), but there is a need for hundreds or thousands of such products, as in the 2D world. Having access to multiple tools that work with open file formats is invaluable because it gives you the freedom to customize to your specific needs. Closed formats and proprietary solutions will not provide such freedom. Ultimately, data in database or CSV format, plus geometry in glTF or USD format, is more flexible. There is a critical need for a universal data exchange format. For now, only the IFC standard is in place, but even it depends on a geometry kernel.

3.2 IFC

IFC originated at the Technical University of Munich. In 1994, a new organization, IAI, was formed to develop classification rules for IFC derived from the STEP format. In 2005, it became buildingSMART (Laakso & Kiviniemi, 2012). IFC has two main parts: meta information stored in EXPRESS tags and a geometric part (Ismail, Nahar, & Scherer, 2017). The history of meta information in EXPRESS tags dates back to the punch cards of the late 1970s. However, the geometric part, which requires a so-called geometric kernel, is particularly interesting. While the meta information from an IFC file can be opened in an ordinary text editor, the geometric data is described parametrically elements such as walls or windows are defined by points, lines and vectors, which requires advanced mathematical calculations. This complexity is due to the fact that it was decided to use the same geometric kernels for the construction industry as for CAD in mechanics. In mechanical engineering, we have extremely complex geometric challenges that require precision, hence these massive kernels, and we're talking about tens of millions of lines of code. By comparison, OpenCascade, the only open-source geometric kernel available (Liu et al., 2023), has 20 million lines of code - an astronomical amount even for complex systems. The irony is that in construction, we rarely need this level of complexity and precision. In the vast majority of cases, geometry at LOD (Level of Detail according to AIA) 200 or even LOD 100 is sufficient. In AECOO, there is no need for precise representation of welds or bolt threads (the phenomenon of overmodeling).

BIM specialists promote IFC as a universal solution, overlooking a fundamental problem: every IFC implementation relies on geometric kernels - the complex mathematical engines necessary to handle parametric geometry. Without these kernels, it is simply impossible to process geometric data. Moreover, these kernels were developed by different teams in different countries, each using their own mathematical approach (Ingram, 2020). You can't simply combine these different parametric formats - they are fundamentally incompatible with each other. This creates an interesting paradox: even if companies wanted to make their formats truly open, this would not solve the problem, because the underlying architecture is too complex and fragmented to be usable. The architecture of the IFC format, despite its claimed openness, relies on a deeply coded computational layer that requires interpretation by a specialized geometric kernel. Geometric data is written in a parametric way - walls, windows or beams are described not directly, but by points, vectors and topological operations (e.g. extrude, revolve, boolean). The layer diagram shown (Fig. 1) illustrates the complexity of IFC and the simplicity of glTF/USD.

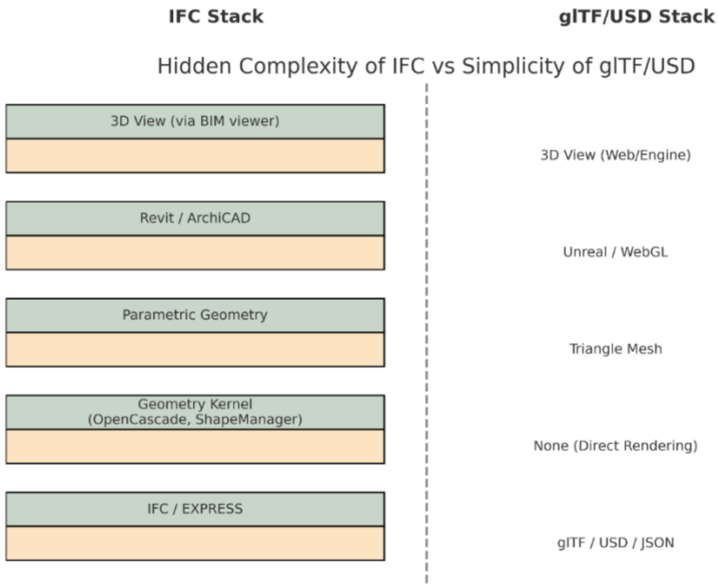

Figure 1: Layer diagram showing the complexity of IFC vs. the simplicity of glTF/USD.

It is the geometric kernels, e.g. OpenCascade, Shape Manager (Yan et al., 2011), that are responsible for processing data into a 3D model. The lack of compatibility between different kernels prevents full interoperability - despite formal compatibility with IFC. Nor has the problem been solved by the proliferation of CDE platforms or SaaS services.

3.3 CDE/SaaS

CDE has been a mainstay of data management in the BIM industry for many years, offering a central repository where documents, models, and project-related data were stored (Borkowski et al., 2023). The CDE provides a single source of truth within an organized structure and allows for version control and access management (Radziejowska, Ciepłucha, & Majta, 2025). However, the approach is still based on storing data in traditional files (Dolla, Venkatachalam & Kumar Delhi, 2024), which has its limitations in terms of flexibility and integration with other systems. The diagram (Fig. 2) shows a comparison between the traditional CDE model, based on closed data repositories, and modern solutions based on structured data and open standards. This change has the potential to reduce the reliance on a central repository and to allow direct access to the data and easier processing in various analytical environments and AI tools. The comparison uses a qualitative ordinal scale (Low / Low–Moderate / Moderate / Moderate–High / High), reflecting the author's expert judgement based on the analysis presented in this paper. The ratings are based on the author's expert judgement, derived from the comparative analysis of workflows, platforms and data models presented in the Materials and Methods and Results sections; they are intended to illustrate relative tendencies rather than statistically validated measurements.

To ensure transparency of the assessment, Table 1 presents the evaluation criteria used for scoring. Each dimension was assessed on a five-level qualitative ordinal scale, where the boundary values are defined as follows:

Table 1: Evaluation criteria for comparative scoring of data paradigms.

Dimension	Low	Moderate	High
Kernel dependency	Fully dependent on a proprietary or complex geometric kernel for any data access	Kernel required for geometric operations but not for attribute access; partial workarounds available	No kernel required; data readable by any standard parser
Openness / portability	Closed, vendor-locked format; requires licensed software	Open specification but with complex dependencies that limit practical portability across platforms	Fully open specification; readable across platforms without licensing
Geometry–attribute separation	Geometry and non-geometric data tightly coupled in a single structure	Partial separation possible through export routines, but not natively supported by the format	Geometry and attributes stored independently with stable identifiers
AI / real-time compatibility	Cannot be directly ingested by AI frameworks or real-time engines without extensive conversion	Usable by AI or real-time engines after moderate conversion effort or with plugin support	Natively supported by AI pipelines, game engines and simulation platforms
Scalability	Performance degrades significantly with project size; limited streaming support	Handles medium-scale projects adequately; streaming or distributed processing possible but not native	Supports large-scale streaming, aggregation and distributed processing

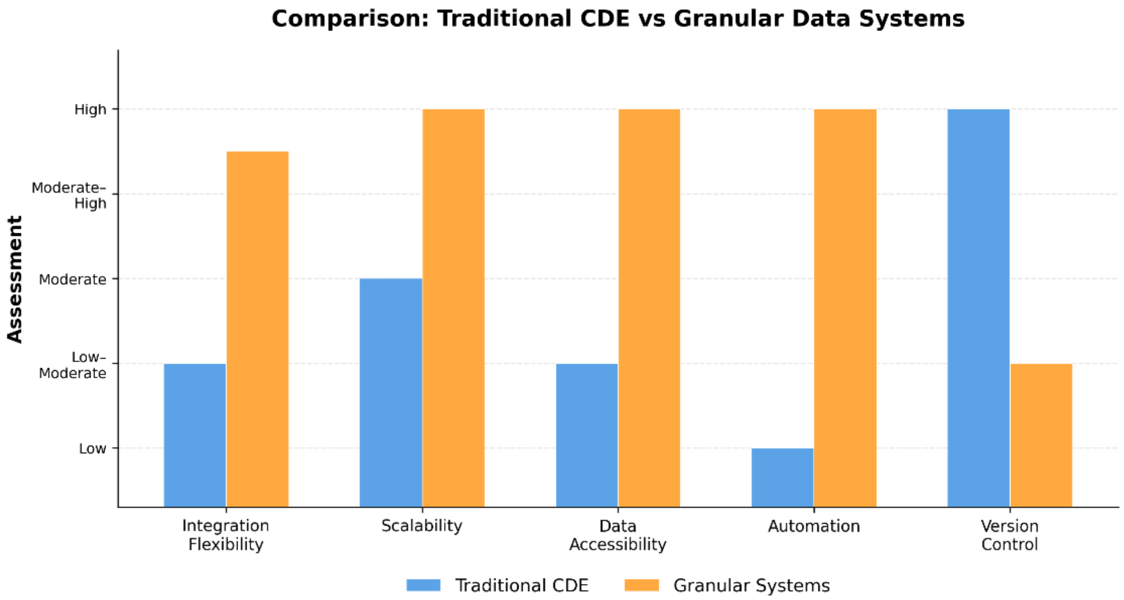

Figure 2: Comparison of traditional CDE and new data systems.

Instead of relying on CDE intermediation that forces export to files and interaction with closed formats (e.g. Revit, Allplan, etc.), the modern approach is to use structured data such as USD, glTF, JSON, SQL, which eliminates dependence on specific platforms and allows direct integration with a variety of systems and tools. In turn, the chart (Fig.3) illustrates the performance of data integration in traditional CDEs and new granular systems. It can be clearly seen that in traditional systems with a central repository, integration is much more time-consuming and costly, as it requires data processing at different stages of the project, as well as continuous export and import of data between different platforms.

Finally, changes in the granular data paradigm enable easier automation of design processes, as well as efficient training of AI models. Open data formats, such as USD and glTF, allow data to be used dynamically in different environments, which is becoming crucial in the era of digital twins and autonomous building systems.

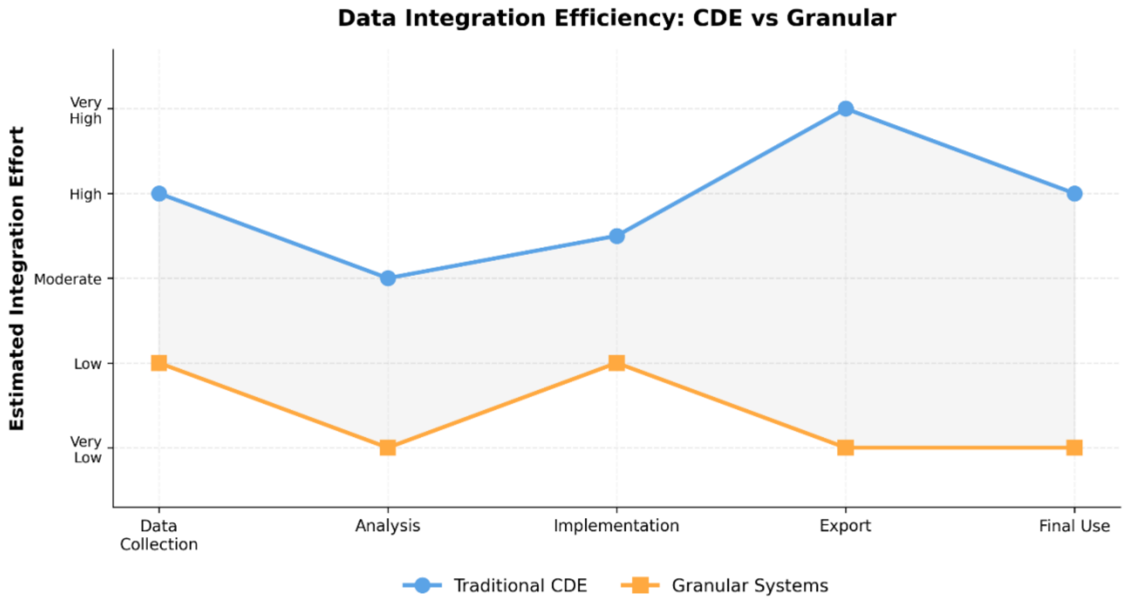

Figure 3: Performance of data integration in CDE vs. granular systems.

3.4 Game Engines (glTF, USD)

The evolution of game engines has been dogged by the success of platforms such as Unreal Engine and Blender, which operate on triangular geometry. NVIDIA saw potential beyond just meta information and basic structures, wanting advanced 3D modeling capabilities without the burden of complex geometric kernels. The breakthrough came with the glTF format, an open standard developed by an alliance including giants such as IKEA and Facebook and originally created by Sun Microsystems. A key innovation is the shift from parametric geometry to a triangular mesh. This shift has allowed architects to move from traditional tools to environments like Unreal Engine, where they can work directly on visualizations, simulations and calculations. The potential of such environments is enormous, and examples of implementations include the digital twins of SNCF stations in France, Palermo and Kaohsiung in Taiwan built in NVIDIA Omniverse (NVIDIA, 2025). These platforms also extend beyond visualisation, as they can process because the platform can process billions of triangular meshes and train AI agents for building applications. The Fraunhofer Institute is already using the system to train robots in virtual environments before they hit real construction sites (IPA, 2025). These examples illustrate the direction of emerging practice rather than constitute systematic evidence, but they suggest a potentially significant shift in the approach to geometric data. Instead of relying on complex geometric kernels like Open CASCADE or Shape Manager, with hundreds of millions of lines of code, the work is done on simple triangular grid data. It's like going from a complex Photoshop file and native PSD format to a simple and lightweight PNG. It's an approach that is more accessible, efficient and practical for real-world applications.

The USD format, on the other hand, was developed by Pixar Studio (Hecht et al., 2021). The idea was based on the premise that since the format can handle complex film animation, it can also handle construction site modeling. This is a great example of how an innovation from one industry can significantly influence another. Game engines such as Unreal Engine, Unity and Omniverse from NVIDIA have evolved from rendering platforms into full-fledged data environments capable of real-time simulation, interaction and geometric analysis. Their huge advantage over traditional BIM systems is their native operation on triangular meshes, which are not only computationally lightweight, but also easy to integrate with AI, sensors, robotics and augmented reality. Unlike classical models based on geometric kernels, data in glTF or USD formats can be accessed directly and processed by various engines without the need to read geometry in a proprietary way. This approach opens the possibility of training AI agents, dynamic scenario testing and even virtual site management.

With support from companies such as NVIDIA, Apple and IKEA, glTF and USD formats glTF and USD formats are increasingly positioned as potential next-generation standards — analogous to PDF, but for spatial data. Their modular architecture and streaming capabilities mean that game engines are not only ahead of BIM in terms of interactivity but may, in certain use cases, serve as alternatives to classic model viewers. This suggests that proprietary formats may not always be necessary, as open standards like glTF appear capable of serving certain needs effectively.

This approach may help address two longstanding barriers in the AECOO industry: (i) the need to hire specialized personnel and (ii) the purchase of expensive licenses. As open formats proliferate, this could lead to a proliferation of new solutions. The real challenge will be the willingness of companies to train employees on these new digital tools. This puts traditional suppliers in a challenging position, as their current business model may need to adapt significantly to accommodate this change. The promoted concept of granular data, which involves a move away from file-based systems and toward structured data, may increasingly resonate.

3.5 Limitations of mesh-based formats (glTF, USD)

While mesh-based formats such as glTF and USD offer significant advantages in terms of openness, portability and real-time performance, they are not a universal solution for all design and engineering tasks. Their adoption entails a number of trade-offs that need to be explicitly acknowledged when considering a transition away from parametric, kernel-based representations (Soemantoro & Margetts 2025).

First, mesh-based formats inherently operate on discrete triangular (or polygonal) approximations of geometry. This leads to a loss of parametric intelligence: relational constraints, construction histories, feature trees and semantic design intent (e.g. alignment rules, parametric dependencies between elements) are typically not preserved in a directly usable way (Pratt, Anderson & Ranger 2005). As a result, operations such as late-stage design changes, rule-based regeneration or parametric optimisation must be performed in the original authoring environment, not in the mesh-based representation.

Second, meshes are subject to a precision–complexity trade-off (Kniat 2014). High-fidelity representations of curves, NURBS surfaces or complex junctions require dense triangulation, which increases file size and computational load. Conversely, lighter meshes reduce data volume but introduce geometric approximation errors that can be unacceptable for certain use cases, such as detailed engineering analysis, tolerance-sensitive fabrication, or clash detection at fine scales. In these contexts, kernel-based parametric models still provide superior numerical accuracy and robustness.

Third, there is a risk of data bloat and fragmentation when mesh-based formats are used as the primary vehicle for exchanging and storing design information. Without a clear strategy for separating geometry from non-geometric attributes, projects can accumulate multiple parallel mesh exports at different levels of detail, for different purposes and platforms (Abualdenien & Borrmann, 2019). This can complicate governance, version control and traceability of changes, especially when meshes are edited independently of the authoritative parametric models.

Finally, the transition to mesh-centric workflows may introduce integration challenges with existing regulatory, contractual and engineering practices that assume access to parametric or drawing-based outputs. Many codes, approval processes and liability frameworks are still tied to traditional deliverables and to the semantics embedded in BIM authoring tools. In practice, this implies that mesh-based formats are more likely to play a complementary role supporting visualisation, simulation, robotics and AI (Zhu, Pauwels & De Vries, 2023) rather than immediately replacing parametric models in all phases of the project lifecycle.

For these reasons, glTF and USD should be viewed not as a complete substitute for kernel-based BIM representations, but as powerful components of a broader, multi-representation ecosystem. Their strengths are most apparent in scenarios that prioritise openness, streaming, real-time interaction and large-scale integration with AI and cyber-physical systems, while precise parametric models remain essential for many core engineering tasks.

3.6 Hybrid data workflows: combining parametric and mesh-based representations

The limitations of mesh-based formats do not imply that kernel-based, parametric BIM representations should simply be replaced. Instead, they point towards the need for hybrid workflows that exploit the respective strengths of both paradigms. In such workflows, precise, constraint-based geometry and design intent remain in parametric models, while lightweight, openly accessible meshes are used to support real-time visualisation, simulation, robotics and AI-driven analytics (Zaman et al. 2024).

A first hybrid strategy is parallel representation (Soemantoro & Margetts 2025; Caporalini 2023). Here, the project maintains an authoritative parametric model (e.g. in a BIM authoring tool or IFC-based environment) and, in parallel, a derived mesh representation in glTF or USD. The parametric model is used for activities that require accuracy and semantic richness – such as engineering analysis, regulatory submissions or detailed coordination – whereas the mesh representation serves applications that benefit from streaming, scalability and platform independence, including digital twins, virtual commissioning or AI training. Consistency between the two representations is ensured by controlled export routines and explicit versioning rules. A second strategy is selective conversion. Not all building elements require the same level of geometric fidelity. Highly detailed or performance-critical components (e.g. structural connections, complex façades, prefabricated systems) can remain in a parametric form for as long as needed, while more generic elements (e.g. partitions, basic architectural components or context models) are converted early to mesh-based representations. This reduces the risk of unnecessary data bloat in meshes and focuses computational resources on the elements where precision truly matters.

Table 2: Comparative summary of IFC (kernel-based), mesh-based (glTF/USD) and hybrid data paradigms.

Criterion	IFC (kernel-based)	Mesh-based (glTF / USD)	Hybrid approach	Evidence / Source
Geometric representation	Parametric (points, vectors, Boolean operations)	Triangular mesh (discrete approximation)	Parametric for precision-critical elements; mesh for visualisation and simulation	IFC schema documentation; glTF 2.0 specification; Pratt, Anderson & Ranger 2005
Kernel dependency	High – requires OpenCascade, Shape Manager or equivalent	None – geometry stored as vertices and faces	Partial – kernel used only where parametric precision is needed	Ingram 2020; Liu et al. 2023 (OpenCascade); author's implementation experience
Openness	Formally open standard, but geometric layer is complex and kernel-dependent	Fully open; supported by broad industry alliances	Mixed – combines open mesh layer with proprietary or open parametric layer	IFC/buildingSMART documentation; Khronos Group (glTF); Pixar (USD) specifications
Semantic richness	High – EXPRESS-based metadata, property sets, relationships	Low to moderate – limited built-in semantics; attributes stored externally	High – semantics retained in parametric model; linked to mesh via identifiers	Ismail, Nahar & Scherer 2017; glTF 2.0 extras/extensions specification
AI / real-time readiness	Low – requires conversion and kernel processing	High – natively supported by game engines, AI frameworks	High – mesh layer directly available for AI; parametric layer for engineering tasks	NVIDIA Omniverse documentation; IPA 2025; Zaman et al. 2024
Scalability / streaming	Limited – file-based, difficult to stream	High – designed for streaming and large-scale scenes	High – mesh layer streams; parametric layer accessed on demand	USD layering architecture (Hecht et al. 2021); Dolla, Venkatachalam & Kumar Delhi 2024
Precision / design intent	High – full parametric history and constraints preserved	Low – approximation only; design intent lost	High for critical elements; acceptable approximation for others	Pratt, Anderson & Ranger 2005; Kniat 2014; Soemantoro & Margetts 2025
Industry adoption	Established in AECOO; mandated by many governments	Growing – driven by gaming, film, digital twins	Emerging – practical implementations increasing	Laakso & Kiviniemi 2012; NVIDIA 2025; Caporalini 2023
Typical use cases	Engineering analysis, regulatory submissions, detailed coordination	Visualisation, digital twins, robotics training, AI workflows	Full project lifecycle – combining strengths of both paradigms	Zhu, Pauwels & De Vries 2023; Ahn et al. 2025; author's project experience

A third approach is decoupling geometry from non-geometric data. In this pattern, the geometric description is handled by formats optimised for 3D rendering and simulation (glTF, USD), while attributes, classifications, time–cost data and operational parameters are stored in structured formats such as JSON, CSV or SQL databases. Links between geometry and data are maintained through stable identifiers. This allows analytical and AI workflows to operate primarily on tabular or graph-based data, while still being able to reference and visualise the relevant geometry when needed. Hybrid workflows can also leverage USD as a layering and referencing mechanism. In this scenario, USD does not replace BIM models but acts as an integration layer (Ahn et al. 2025) that references geometry and attributes originating from multiple sources, including parametric tools, IoT systems and external databases. This enables scenario testing, aggregation and simulation without forcing a single monolithic representation of the project.

From a practical standpoint, hybrid strategies acknowledge existing contractual, regulatory and organisational constraints in the AECOO industry. They make it possible to gradually introduce mesh-based, granular data systems alongside established BIM and CDE practices, rather than requiring a disruptive, all-or-nothing transition. In this way, the industry can benefit from the openness and scalability of glTF/USD-centric workflows, while still relying on parametric models wherever high precision, traceability and rich semantics are indispensable.

To consolidate the comparative findings, Table 2 summarises the key characteristics of the three data paradigms discussed in this paper.

3.7 Limitations and future research direction

While this paper is based on a wide range of industry experience and literature review, it does not include empirical validation through controlled experiments or surveys. The conclusions are drawn from qualitative analysis and case-based reasoning. Moreover, the focus is on commercial design workflows and open standards rather than proprietary innovations from specific vendors. Future research should explore how granular data and open formats perform across various project scales and disciplines in practice.

Future studies should investigate how granular data systems perform in real-world, multidisciplinary projects. This includes evaluating their interoperability with legacy systems, the scalability of AI-based workflows, and the governance of data ownership in decentralized environments. Additionally, standardizing methods for converting parametric data to mesh-based formats without loss of fidelity remains an open technical challenge. Collaborations between academia, software developers, and regulatory bodies will be key to advancing these areas.

4. CONCLUSION

The transformation described in this paper, from files and parametric models to granular data and triangular grids, can be understood as more than a change in format, it points toward a potential redefinition of information architecturein construction. It calls into question the assumption that interoperability can be solely achieved through formal standards (such as IFC), while ignoring the computational back-end of these formats This shift from SaaS to direct data access has the potential to fundamentally reshape the AECOO industry. There is a shift from complex, clickable interfaces to simple, data-driven workflows that can be automated and enhanced with artificial intelligence. The future of digital practice in the AECOO industry is likely to be less about mastering specific software products and more about developing robust strategies for effective data management.

The results of the analysis show a shift away from dependence on geometric kernels to direct access to data in simple, structured formats that can be converted between USD, glTF, COLLADA, OBJ or OpenGL, while data storage can be implemented in various forms: SQL, XML, JSON. IFC is likely to persist, not necessarily because it is the optimal solution, but because it benefits from the support of the support of major CAD/BIM vendors, consulting firms and increasingly, governments. They are promoting OpenBIM and IFC formats, the complexity of the geometric kernels and tools required in the background should not be overlooked. Within the next decade, it is plausible that robots and autonomous systems will play an increasingly central role on construction sites, supporting or partially replacing selected human-operated tasks. These robots are unlikely to require parametric geometry; instead, they would benefit from flat, structured data from thousands or even millions of projects to effectively train AI models.

True openness may require just access to the structure of the data, but also the ability to read, analyze and automate it without depending on closed geometric kernels. Open, lightweight formats like glTF or USD, supported by game engines and AI environments, appear to offer considerable potential compared to traditional BIM solutions. Therefore, a reorientation in BIM development appears both plausible and increasingly supported by emerging evidence. Tools would need to open up for conversion, translation, export and similar operations if this trajectory is to materialise. For design practice, this means being able to build hybrid environments that combine design, simulation, costing and real-time execution data. For the scientific community, it suggests a needfor new methodologies for managing and analyzing design data that are independent of applications and geometric kernels.

These findings are of particular relevance to several groups of stakeholders. For AECOO practitioners and project managers, the analysis highlights that reducing dependency on geometric kernels and proprietary formats can lower barriers to data access, simplify integration with AI-driven tools, and reduce licensing costs. For software developers and platform providers, it signals a growing demand for open, kernel-independent data pipelines that support real-time collaboration and interoperability across heterogeneous environments. For BIM researchers and the academic community, it reframes the interoperability challenge as a computational-infrastructure problem rather than a schema-mapping problem, opening new avenues for investigation.

The conclusions of this paper also point to several directions for future research. The case examples presented in this paper, including digital twin deployments and robotic simulation environments, are illustrative rather than analytically generalisable, and the conclusions drawn from them should be treated as plausible hypotheses rather than established findings. Empirical studies are needed to validate whether mesh-based and granular data workflows deliver measurable improvements in interoperability, cost efficiency and scalability across diverse project types and scales. Methods for converting parametric BIM data to mesh-based representations without critical loss of geometric fidelity and semantic richness require further development and standardisation. Finally, the governance, contractual and regulatory implications of transitioning from file-based CDE systems to decentralised, structured-data environments remain largely unexplored and warrant dedicated investigation.

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